Three-dimensional finite element analysis of the influence of different surgical methods on the stress of meniscus and patellofemoral joint in the treatment of episodic patellar dislocation

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Research Article

Keywords: Episodic patellar dislocation, Medial patellofemoral ligament reconstruction, Patellofemoral joint, Biomechanics, Finite element analysis

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**Abstract**

**BACKGROUND:** At present, there are many surgical methods for the treatment of episodic patellar dislocation, and it is still unclear which surgical method can provide appropriate meniscus and patellofemoral joint stress.

**OBJECTIVE:** To explore the influence of different surgical methods simulating episodic patellar dislocation in three-dimensional finite element software on the stress of knee meniscus and patellofemoral joint surface under different flexion conditions.

**METHODS:** Acquire the knee joint CT and MRI of patients with episodic patellar dislocation and import them into Mimics and Geomagic to extract the model, then use Solidworks to complete the 0 °, 30 °, 60 °, 90 ° and 120 ° buckling construction of the model, for each model, medial patellofemoral ligament reconstruction, medial retinaculum plication, lateral retinaculum release, medial patellofemoral ligament combined with medial patellotibial ligament reconstruction, medial patellofemoral ligament reconstruction combined with lateral retinaculum release be operation respectively. Finally, the model is imported into the mechanical software Ansys for biomechanical analysis, and the stress results of knee meniscus and patellofemoral joint surface are output.

**RESULTS:** The medial patellofemoral ligament combined with medial patellotibial ligament reconstruction has the smallest meniscus stress compared with other methods. The medial patellofemoral ligament combined with medial patellotibial ligament reconstruction and the medial patellofemoral ligament reconstruction combined with the lateral retinaculum release have smaller stress on the patellofemoral joint surface compared with the other three methods.

**CONCLUSION:** The medial patellofemoral ligament combined with medial patellotibial ligament reconstruction can provide well patellofemoral contact stress and meniscus stress, effectively restore the stability of the knee joint, and delay the purpose of joint and cartilage degeneration. Medial patellofemoral ligament reconstruction combined with lateral retinaculum release can also provide better patellofemoral joint stress, but the meniscus stress is slightly higher, so we should be alert to the complications related to the meniscus after surgery. Due to the high stress between patellofemoral joints and meniscus, the medial patellofemoral ligament reconstruction should prevent the risk of redislocation and the high incidence of patellofemoral osteoarthritis.

**Introduction**

*Episodic* patellar dislocation (EPD) is a common knee joint sports injury in clinic[1]. It refers to the transient dislocation of the patella repeatedly caused by trauma. Usually, it can be reset by bending the knee. It often occurs in teenagers, especially in women[2, 3]. For EPD, surgical treatment has become the main measure recognized by most authors. The purpose of the operation is to restore the stability of the patella, restore appropriate patellar joint pressure, and slow down osteoarthritis caused by knee degenerative disease. Now there are hundreds of surgical methods in clinical practice, which can be
divided into two types according to the tissue type: first, reconstruction of the ligament; second, correction of the bone deformity. Usually the reconstruction of the ligament can solve most problems. The reconstruction of soft tissue is basically carried out around the reconstruction of medial patellofemoral ligament (MPFL). Because MPFL provides 50%~60% resistance to limit patella exodus[4]. MRI studies also showed that 98.6% of patients with patellar dislocation had MPFL injury[5, 6]. In clinical practice, we have successively carried out medial patellofemoral ligament reconstruction (MPFLR), medial retinaculum plication (MRP), lateral retinaculum release (LRR), medial patellofemoral ligament combined with medial patellotibial ligament reconstruction (MPFLR+MPTLR), medial patellofemoral ligament reconstruction combined with lateral retinaculum release (MPFLR+LRR) to treat EPD. There is no definite conclusion on which surgical method can provide better prognosis for patients[7]. 3D finite element uses CT or MRI of the human body to convert the 2D human tomographic image into a solid, making the operation digital, repeatable operation and simulation, overcoming the shortcomings of traditional biomechanical materials that cannot be reused, and making the research simple and easy. 3D finite element can also provide clear biological tissue, which can be operated and dissected at any angle to complete basic surgical operations. Moreover, the effectiveness of 3D finite element has been recognized by many fields, and it is widely used in many fields such as stomatology, orthopedics, cardiovascular, etc[8, 9]. Virtual biomechanics based on 3D finite element is gradually replacing traditional mechanical testing, and has achieved good research results in many fields. In our study, the 3D finite element software was used to simulate different surgical methods of recurrent patellar dislocation, and then the influence of various surgical methods on the meniscus and patellofemoral joint stress under different flexion degrees was calculated through Ansys to provide some reference for clinical treatment.

Materials And Methods

A young male patient with EPD, aged 20 years, BMI 23.6kg/. This case has the following characteristics: Dislocation of patellofemoral joint more than twice; Physical examination: Patella tilt test (+); Fear test (+); Imaging examination (knee flexion 45° patella axial film and CT) showed that the distance between the tibial tubercle and the intertrochanteric groove (TT-TG) was ≤20 mm, there was no severe dysplasia or deformity of the femoral trochlear and abnormal patellar position, and the epiphysis was closed; There was no history of surgical treatment for patellar dislocation in the knee; No multiple ligament relaxation (Beighton score>4). CT and MRI were used to perform thin slice scanning (1mm thick) 15cm above and below the knee joint to obtain DICOM format imaging data. The experimental scheme has been discussed and approved by the Ethics Committee of the First Affiliated Hospital of Xinxiang Medical University, informing the volunteers of the risks and precautions, and signing the informed consent form after obtaining the consent.

Import DICOM format image data into Mimics software. According to different CT values and MRI signal values of tissues, bones, ligaments and meniscus can be distinguished; The 2D tomographic images are transformed into 3D solids, and the broken ends of bones are filled to obtain the closed model. The 3D model of knee joint generated initially is the unpersonalized point cloud data, whose surface has defects
and protrusions. It is necessary to smooth and wrap the 3D model for the first time, and finally save and output it in STL format. (Figure 1)

The generated initial generation knee joint model (Figure 2) is disassembled and imported into Geomagic software to remove the surface protrusions and repair and fill the depressions. The bone surface is smoothed again to increase the surface texture, divide the area and carry out grid doctor treatment for each tissue structure, repair the incomplete cavity, accurate curved surface, and redraw the contour line to implement curved surface, which can be converted into a solid; Each bone of the knee joint is materialized according to the above operations in turn, and the output is saved in the 3D general format STP. Figure 3.

Simulated surgery

The models generated from Geomagic software are opened and run in the software Soildworks to unify the origin for assembly. The models of 0°, 30°, 60°, 90° and 120° are assembled successively through the software function of moving and copying entities. Because the fibula has no effect with the experiment, the fibula entity is deleted. In order to verify the effectiveness of the bone model without added ligaments, the model was introduced into Ansys, the femoral end was restrained and fixed, the tibia was restrained and fixed at the knee flexion position of 0°, other contacts were not restrained, and 134N forward thrust load was applied at the center point of the tibia, and the forward displacement of the tibia in the vertical position of the model was calculated to be 4.89mm. Under the same conditions, the research result of Gabriel et al[10] is 5.0 mm; Pena et al[11] showed that the tibia moved forward by 4.75 mm, so the measurement results of this entity were similar to those of others. It is proved that the established the model of the knee joint is qualified and effective, which can be used for subsequent research. Simulated operation implementation and ligament establishment in Soilwork. MPFLR model (A): the lateral patellar insertion is established at the middle upper edge of the patella, and the femoral insertion is established at the midpoint of the femoral medial epicondyle and adductor tubercle, the reconstructed medial patellofemoral ligament was generated by the lofting function of the software; MRP model (B): In this project, the medial patellofemoral ligament was shortened from the initial measurement of 62 mm to 56 mm until the patella surface was aligned with the femoral surface; LRR model (C): lengthen the patellar edge of lateral patellar retinaculum by 5mm until the patellar surface and femoral surface fit (multi angle observation); MPFLR+MPTLR model (D): repeat operation A to reconstruct MPFL, then take the medial 1/3 of patellar ligament at the lower pole of the patella to the tibial tubercle, and then lay out to the medial side of the tibial platform; MPFLR+LRR model (E): repeat A and release the lateral retinaculum until the patella surface and femoral surface fit. Introduce the model into Ansys, apply 70N tension to quadriceps femoris tendon, bind the tibia end, and obtain the patellofemoral joint stress of each model in vertical position as 1.39Mpa, 1.39Mpa, 1.41Mpa, 1.38Mpa, 1.42Mpa. It is basically consistent with the patellofemoral pressure test result (1.41Mpa) of Li Yanlin's fresh frozen cadaver knee joint in the straight position[12], which once again verifies the effectiveness and authenticity of the model. (Figures 4 and 5 show the model D and E)
In the Ansys software, set the elastic modulus of bone to 14357MPa and Poisson's ratio to 0.34; The elastic modulus of cartilage is 20MPa, and Poisson's ratio is 0.46; The elastic modulus of meniscus is 59 MPa and Poisson's ratio is 0.49[13]. Ligaments are defined as hyperelastic materials, Material relationship is Neo Hook model. The Neo-Hook constant of medial patellofemoral ligament and lateral patellar retinaculum is 1.44, and the compressible parameter D is 0.00126[14]; The Neo-Hook constant of patellar ligament, quadriceps tendon and reconstructed medial patellotibial ligament is 2.75, and the compressible parameter D is 0.00484[15-17]. See Table 1 and Table 2. Set the bone grid as 5mm, and the ligament, meniscus and cartilage grid as 1mm. Figure 6.

Set the position at the bottom of the tibia end to fix, the femur is not constrained, and the patellofemoral joint surface and meniscus contact surface are set to be frictionless; The contact between ligament and bone surface is binding. The anterior and posterior cruciate ligaments and the medial and lateral collateral ligaments were replaced by linear springs. The maximum tension produced by the quadriceps tendon ranges from 1238.9 to 1333.0N, so 1300N axial tension is applied to the quadriceps tendon; Axial load of 600N applied to the proximal end of femur is equivalent to the force generated by standard adult weight.

**Table 1** Material assignment

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>bone</td>
<td>14357 MPa</td>
<td>0.30</td>
</tr>
<tr>
<td>cartilage</td>
<td>20.0 MPa</td>
<td>0.46</td>
</tr>
<tr>
<td>meniscus</td>
<td>59.0 MPa</td>
<td>0.49</td>
</tr>
</tbody>
</table>

**Table 2** The material parameters of the ligaments

<table>
<thead>
<tr>
<th>Ligament</th>
<th>Neo-Hooke constant</th>
<th>Compressible parameter D</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPFL</td>
<td>1.44</td>
<td>0.00126</td>
</tr>
<tr>
<td>Lateral patellofemoral retinaculum</td>
<td>1.44</td>
<td>0.00126</td>
</tr>
<tr>
<td>Patellar ligament</td>
<td>2.75</td>
<td>0.00484</td>
</tr>
<tr>
<td>Quadriceps tendon</td>
<td>2.75</td>
<td>0.00484</td>
</tr>
<tr>
<td>Patellotibial ligament</td>
<td>2.75</td>
<td>0.00484</td>
</tr>
</tbody>
</table>

**Results**

MPFLR+MPTLR has the smallest meniscus stress peak compared with other methods.
Through the Ansys statics analysis, the maximum stress peak value was output. We found that among the five surgical methods, MPFLR + MPTLR have the minimum stress peak value at different flexion degrees, while MRP have the maximum stress peak value. Observing the maximum peak value of meniscus at different angles, it can be found that the peak value of meniscus stress increases with the increase of buckling angle, which also conforms to the structure of human body mechanics vector. Exploring the distribution range of the cloud map, it was found that the stress of 0° and 30° half moon was mostly concentrated on the front edge of the inner and outer meniscus, and the five surgical methods remained the same. At 60°, the stress of the medial meniscus after MPFLR and LRR concentrated in the posterior corner in advance, while other three methods concentrated in the anterior lateral part. Table 3, Figure 7 and Figure 8.

Table 3: Maximum stress peak value of meniscus under different knee joint flexion of models with different surgical methods (Mpa)

<table>
<thead>
<tr>
<th>Knee flexion angle</th>
<th>0°</th>
<th>30°</th>
<th>60°</th>
<th>90°</th>
<th>120°</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPFLR model</td>
<td>4.40</td>
<td>5.67</td>
<td>6.45</td>
<td>7.18</td>
<td>8.18</td>
</tr>
<tr>
<td>MRP model</td>
<td>4.70</td>
<td>6.35</td>
<td>7.33</td>
<td>8.20</td>
<td>9.11</td>
</tr>
<tr>
<td>LRR model</td>
<td>4.50</td>
<td>6.05</td>
<td>6.84</td>
<td>7.69</td>
<td>8.74</td>
</tr>
<tr>
<td>MPFLR+MPTLR model</td>
<td>4.32</td>
<td>4.60</td>
<td>5.52</td>
<td>6.11</td>
<td>7.34</td>
</tr>
<tr>
<td>MPFLR+LRR model</td>
<td>4.41</td>
<td>4.96</td>
<td>5.76</td>
<td>6.50</td>
<td>7.80</td>
</tr>
</tbody>
</table>

MPFLR+MPTLR and MPFLR+LRR have smaller stress peaks on the patellofemoral joint surface compared with the other three methods.

Analyzing the output peak stress between patellofemoral joints, it is found that MPFLR+MPTLR and MPFLR+LRR have smaller peak stress on patellofemoral joint surface under different knee flexion degrees, and their D-value ranges from 0.06 to 0.22Mpa, which is not significant. The MRP model has the maximum stress value of patellofemoral joint surface no matter what angle the knee joint flexes. It was found that the peak stress of patellofemoral joint surface increased with the increase of angle during the change of 0° ~90°. Based on the distribution of the stress cloud, the stress on the patellofemoral joint surface is concentrated in the upper and middle part, reconstruction at the medial margin of the inferior patellar pole, however, only partial stress in the MPFLR+MPTLR model appears at the medial edge of the inferior patellar pole. Table 4, Figure 9, Figure 10

Table 4: Maximum stress peak value (Mpa) of patellofemoral joint surface under different knee flexion conditions of models with different surgical methods
<table>
<thead>
<tr>
<th>Knee flexion angle</th>
<th>0°</th>
<th>30°</th>
<th>60°</th>
<th>90°</th>
<th>120°</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPFLR model</td>
<td>3.07</td>
<td>3.90</td>
<td>4.77</td>
<td>5.29</td>
<td>4.20</td>
</tr>
<tr>
<td>MRP model</td>
<td>4.81</td>
<td>5.50</td>
<td>6.43</td>
<td>7.31</td>
<td>5.43</td>
</tr>
<tr>
<td>LRR model</td>
<td>3.77</td>
<td>4.40</td>
<td>5.33</td>
<td>6.26</td>
<td>4.35</td>
</tr>
<tr>
<td>MPFLR+MPTLR model</td>
<td>2.99</td>
<td>3.48</td>
<td>4.07</td>
<td>4.62</td>
<td>3.44</td>
</tr>
<tr>
<td>MPFLR+LRR model</td>
<td>3.05</td>
<td>3.26</td>
<td>4.11</td>
<td>4.45</td>
<td>3.53</td>
</tr>
</tbody>
</table>

**Discussion**

Most EPD are MPFL injuries caused by acute trauma, with early mishandling resulting in another or multiple dislocations, characterized by recurrent transient dislocations[18]. The underlying cause of the dislocation is an abnormal anatomic relationship of the patellofemoral joint[19]. The patellofemoral joint plays an important role in flexion extension movements of the knee. The bony structure of the patellofemoral joint, composed of the patella and femoral trochlea. The ligaments and muscles around the patella constitute the static and dynamic stable structures that maintain the patella. So dividing the factors responsible for recurrence on different tissue categories can be divided into two categories; Soft tissue factors: weak medial retinacular laxity, weak medial oblique muscle strength, lateral soft tissue contracture, hypermobile spectrum disorder. Bone factors: patellar shape, high riding patella, patellar tilt, femoral trochlear dysplasia, excessive TT-TG distance, and increased Q angle[6, 20, 21]. Of these two broad categories of contributing factors, soft-tissue factors contribute more to the EPD. The medial and lateral retinaculum is an important structure for static balance in maintaining patellofemoral anatomy, and certainly as dissection techniques have refined, it has become apparent that the MPTL also plays a role in stabilizing the patellofemoral joint[22]. At present, the treatment of EPD is mostly focused on the repair and reconstruction of ligaments, especially the reconstruction of MPFL, Common clinical operation methods include: MPFLR, MRP, LRR, MPFLR + MPTLR, MPFLR + LRR.

In this topic, we will use the three-dimensional finite element software to digitally analyze the five common soft tissue repair and reconstruction operations in clinical practice to see what type of operation can provide a better patellofemoral relationship so as to reduce the stress between patellofemoral joints, prevent the excessive pressure between joints and the abnormal movement of the ligament in the later period, so as to delay the osteoarthritis and degenerative disease of the knee joint. From the results, we found that MPFLR does not address the contact stress of the patellofemoral joint very well, especially its peak stress during 30° - 120° of flexion was 0.42 ~ 0.76Mpa higher than MPFLR + MPTLR. In the meniscal stress cloud diagram, at 60° of knee flexion, the stress appeared earlier at the body of the medial meniscus and part of the posterior horn, much related to the femoral stop point of the medial patellofemoral ligament in reconstruction, which was similar to Flandry's anatomic study of the knee[23]. Advance appearance States advanced compression in the medial half month with narrowing of the gap that worsens the osteoarthritis. The above may also explain why patellofemoral instability still occurs in
12% of patients with MPFLR clinically. MRP was always maximal at both medial and lateral meniscal stress peaks and at the level of the patellofemoral compartment regardless of the degree of knee flexion. Stress has also been shown on the patellofemoral surface cloud to be biased towards the medial patellar border, and tightening of the ligamentum teres, although resolving abnormalities in the trajectory of patellar mobility, increases the area of patella femur contact and pressure, most likely accelerating patellofemoral degeneration and inflammation. LRR has been shown to alter stress to some extent compared with MRP, but there are significant drawbacks when comparing it with MPFLR. The meniscus stress peak was 0.1–0.56 MPa higher at various degrees of flexion, and the patellofemoral surface stress peak was 0.97 MPa higher at 90 ° of flexion. This may be related to greater patellofemoral mobility gap after laxity, and the higher peak also suggests that lateral retinacular release alone does not provide a better patellofemoral contact relationship. MPFLR + MPTLR has the smallest meniscal peak at various degrees of flexion of the knee, which is related to the fact that the reconstructed patellotibial ligament distributes part of the quadriceps bringing tensile force, which in turn reduces meniscal stress. The MPFLR + MPTLR was found to be optimal on the patellofemoral cloud map, although the peak values of stress at 30 ° and 90 ° of flexion were higher than those of MPFLR + LRR at 0.22 MPa, 0.17 MPa, respectively. In addition, part of the stress appeared medial to the inferior pole of the patella, which was affected by the pulling force from the patellotibial ligament, but the cloud map was more evenly distributed, and small stress had little effect on the articular surface. Regarding medial patellotibial ligament (MPTL) studies suggesting a role in dislodging the patella medially, biomechanical studies have found the greatest contribution of the MPTL to patellar stability at greater than 45 ° of knee flexion. It also explains why the MPFLR + MPTLR has lower patellofemoral stress than MPFLR + LRR during 60 ° of flexion. Mani et al also concluded that reconstruction of the MPTL reduces the Q-angle and thus improves patellar excursion while not causing as much tibiofemoral kinematic change as an anterior tibial trochanteric osteotomy. Yang et al, who enrolled 108 patients with recurrent patellar dislocation, found that TT-TG values were significantly lower after MPTLR, and that the lower TT-TG values indicated some degree of internal displacement and internal rotation of the femur, which would directly cause an increase in the contact area between the medial edge of the patellofemoral cartilage surface and also explain why the facial stress distribution of the patellofemoral joint appeared at the inner edge. Meniscal pressure after MPFLR + LRR is slightly higher than MPFLR + MPTLR, but it is significantly reduced compared with MPFLR, with a maximum reduction of 0.71 MPa at 30 ° of flexion. However, the values at other different degrees of flexion were not significantly different from those of MPFLR + MPTLR, and they could provide the smallest peak patellofemoral stress at 30 ° of knee flexion, suggesting that it is also a surgical method to restore the patellofemoral relationship better.

**Limitations And Perspectives Of This Study**

1. The mold was created without incorporation of vastus medialis obliques and other musculocutaneous soft tissues, which may also have influenced the results, with some error compared with real human subjects. Limitations of the software, the reconstruction of part of the ligaments as hand drawn, present certain biases. Limited by technology, the software cannot
dynamically demonstrate the entire dynamic biomechanical process and can only fix the angle statically analyzed. Outlook: this subject did not consider the condition of bony structural abnormalities, at present, our group is ready to investigate the factors such as patellar shape, femoral trochlear dysplasia, and excessive TT-TG distance, targeting the above factors what kind of surgical formula we should adopt will have a good effect, and adding cadaveric knees for verification and comparison to improve the application of 3D finite element.

**Conclusion**

MPFLR+MPTLR can provide good patellofemoral contact stress and meniscal stress, which can effectively restore the stability of the knee joint and delay the purpose of joint and cartilage degeneration. MPFLR+LRR similarly provides superior patellofemoral joint stress, but with slightly higher meniscal stress, with caution for postoperative meniscal related complications. Because of the high stress on the patellofemoral interpatellar and meniscus, MPFLR is required to prevent the risk of re dislocation and the high incidence of complications such as osteoarthritis. The results of this study suggest that EPD are not recommended to be treated by MRP or LRR. Hope this foundational work may provide guidance to clinicians in the treatment of patients with episodic patellar dislocation.

**Declarations**

**Ethical approval and consent to participate**

Ethical standards The study was approved by the Ethics Committee of The First Affiliated Hospital of Xinxiang Medical University, Number: 2022001. The study has been performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

**Availability of data and materials**

All data generated or analysed during this study are included in this published article.

**Informed consent for publication**

Not Applicable

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**Conflict of interest**
All authors of the article declare that there are no conflicts of interest in the research and writing process of the article.

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**Author contribution**

All authors have read and approved the final submitted manuscript. Contributions to authorship are as follows: Biao Xu was responsible for running the computational analysis, interpretation of computational results and contributed to the initial concept for this study, the design of the computational study, analysis, and interpretation of results, and preparing the initial draft of this manuscript. Tan Lu was responsible for guiding clinical inputs to the models and classifying the patients for abnormality and contributed to reviewing the manuscript.

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Tan Lu, M.D., Vice-professor, The First Affiliated Hospital of Xinxiang Medical University, Weihui 453100, Henan Province, China.

**References**


**Figures**

Figure 1

The procession of knee model established by Mimics16.0
Figure 2

The model extracted from Mimics for the first time

Figure 3

femur  

tibia  

patella  

fibula
The procession of knee model established by Geomagic 2017

Figure 4

model for reconstruction of medial patellofemoral ligament combined with medial patellotibial ligament (D), 0°, 30°, 60°, 90°, 120° from left to right

Figure 5

model for medial patellofemoral ligament reconstruction combined with lateral retinaculum release (E), 0°, 30°, 60°, 90°, 120° from left to right
Figure 6

Model after assignment and gridding of medial patellofemoral ligament and medial patellotibial ligament in Ansys 17.0 °, 30 °, 60 °, 90 °, 120 ° from left to right

Figure 7

Stress nephogram of medial and lateral meniscus of knee joint in different flexion degrees after different surgical methods for recurrent patellar dislocation
Figure 8

The broken line diagram of the peak stress of the medial and lateral meniscus produced by different flexion degrees of the knee joint after different surgical methods for the treatment of recurrent patellar dislocation.
Figure 9

Stress nephogram of patellofemoral joint surface caused by different flexion degrees of knee joint after different surgical methods for treatment of recurrent patellar dislocation

The abscissa is the knee flexion angle; The ordinate is the model simulating different surgical methods.
Figure 10

Fracture line diagram of patellofemoral joint peak stress produced by knee joint at different flexion degrees after different surgical methods for treatment of recurrent patellar dislocation