Computer modelling for pre-surgical planning of patellofemoral malalignment treatment

T. Sowiński¹, K. Kietliński²

¹ Military Medical Institute, Department of Orthopaedic, Warsaw, Poland
² Warsaw University of Technology, Institute of Aeronautics and Applied Mechanics, Warsaw, Poland

1. Introduction

One of the known and efficient ways of surgical treatment of the recurrent lateral luxation of the patella is osteotomy of the tibia [1, 3]. The pathology, i.e. the recurrent lateral luxation of patella, takes place due to the patellofemoral joint malalignment. Transposition of the peripheral part of the patellar ligament attachment in the medial and distal directions changes the biomechanics of the patellofemoral joint and prevents from further dislocation. The final decision as to the location where the ligament is to be reattached is taken intraoperatively and is based on empirical methods as well as on the surgeon experience.

The goal of the research presented in the paper is to elaborate a new methodology of tibial tuberosity osteotomy planning. The methodology will allow for virtual planning, optimisation and individualisation of a surgery that is to lead to permanent advantageous changes of biomechanical conditions in the patellofemoral joint, preventing from patella luxation.

2. Methods

The computer-aided methodology presented in the paper aims at improving the patellofemoral malalignment surgery. The need to use the contemporary numerical techniques in detailed modelling of the knee joint to improve the existing surgery technique can be realised by means of a specialised computer system named MADYMO. The software is used for modelling, simulating, visualising and analysing the multi-body and finite element systems behaviours. The computer modelling in the software consists of modelling the mechanically important elements and applying the proper external forces that act on the real object. Then follows numerical computation that yields computer simulation results of the studied real phenomenon and properly defined physical parameters that are important from the biomechanical point of view, such as time changes of forces, moments of force, acceleration etc.

The surgical treatment of the patellofemoral malalignment is mostly based on the transposition of the distal insertion of the patella ligament within a certain area on the tibia tuberosity with respect to its original location. This is meant to reduce the lateral forces acting on the patella that are responsible for the injury. The main difficulty for a surgeon is determining the new, optimal location for the ligament insertion, since the inaccurate or wrong transposition may lead to the ineffective patella luxation treatment, limitations in the knee joint range of motion and thus a number of clinical complications.

The proposed methodology aims at addressing the above mentioned problems, by performing the pre-surgery planning based on the series of computer simulations that replicate the transposition of the ligament insertion followed by orthopaedic testing done in virtual conditions for each individual patient. The results of a series of simulations allow performing the in-depth mechanical analyses for the individual case that is further confronted to the optimization criteria [Tab. 1]. The result of the process is recommendation for a surgeon, delivered in a form of a surgery region map with the new location of ligament insertion. The process of pre-surgery planning:

![Fig. 1 Generic model of the knee joint (left.). The region of virtual surgery (right).](image)
- CT test done for the patient, based on which the bone geometry is generated
- Preparation of multi-body model of the lower limb [Fig 1. left], that includes bones, joint definitions, ligaments of the knee joint, quadriceps muscle, all with pre-defined mechanical properties [2, 4, 5, 6]
- Implementation of the CT-based bone and ligament geometry of the patient into the generic model
- Computation of a series of “virtual surgeries” in which all the possible patella ligament insertion transpositions are tested. Each “virtual surgery” consists of relocation of the ligament insertion followed by an orthopaedic test of the knee joint flexion-extension that is normally done during the actual surgery.
- Analyses of mechanical results with respect to the optimization criteria and generation of the recommendation map with indicated coordinates of transposition vector.
- Actual patellofemoral malalignment surgery based on the recommendation map.

**Table 1 Virtual surgery optimization criteria.**

<table>
<thead>
<tr>
<th>Clinical objective</th>
<th>Tested parameter</th>
<th>Optimization criterion</th>
<th>Criterion value</th>
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<tbody>
<tr>
<td>Patella luxation prevention</td>
<td>Orthopaedic test kinematics</td>
<td>Correct patella behaviour during knee joint flexion-extension</td>
<td>[Correct]/[Incorrect]</td>
</tr>
<tr>
<td>Prevention of clinical complications – excessive articulation forces</td>
<td>Lateral force in femoral patella ligament insertion</td>
<td>Minimal force value</td>
<td>$0 = \text{Force} \leq \text{Ref.}$</td>
</tr>
<tr>
<td>Prevention of clinical complications – range of motion limitations</td>
<td>Total contact force in patello-femoral joint</td>
<td>Force value limited to the reference force</td>
<td>Force $\leq \text{Ref}$; Tolerance = 5%</td>
</tr>
<tr>
<td></td>
<td>Total knee joint flexion angle</td>
<td>Knee joint flexion value equal to the reference angle</td>
<td>Ref. $\leq \text{Angle} \leq 150$; Tolerance = 3 deg</td>
</tr>
</tbody>
</table>

3. Results

The final result of the pre-surgical planning is a recommendation document that includes information on the complete analyses:
1. Evaluation of modelling and simulation correctness based on the visual assessment and physiologically important biomechanical readings defining the correctness of the knee joint bending.
2. Visual evaluation of correctness of patella motion on the femur articulating surface
3. Recommendation maps for each of the optimization criteria.
4. Final recommendation map with commentary, being a result of the analyses of the whole process.

The method was applied in the clinical treatment of seven patients. In case of four, the pre-surgery recommendation correlated well with the final surgery result. For two patients the recommendation could not be made due to the discrepancies in the initial conditions of the simulation resulting from inconsistent CT scanning results. In case of one patient the results were off in medial direction, and there was correction needed.

4. Discussion

The new methodology presented in the paper, proved to effectively assists the pre-surgery process of patellofemoral malalignment clinical treatment. There is a need for further study to improve the CT data acquisition, different types of external loading conditions, geometrical and mechanical properties of model parameters variation to investigate model sensitivity to parameter changes.

References