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Simulation of varying femoral attachment sites of medial patellofemoral ligament using a musculoskeletal multi-body model

Abstract: The medial patellofemoral ligament (MPFL) is a key structure in the treatment of habitual and traumatic patellofemoral instability. However, there exists little knowledge about its behaviour during deep knee flexion after femoral re fixation. Since improper femoral attachment sites may lead to unnatural length change patterns in the ligament and consequently to osteoarthritis due to pathological femoro-patellar contact pressure, the understanding of the patella kinematics and MPFL behaviour is crucial.

The purpose of this numerical study was to compute the six-degree-of-freedom motion pattern of the human patella during deep knee flexion for systematic analysis of varying landmarks for the femoral attachment in medial patellofemoral ligament reconstruction surgery by means of multibody simulation.

Therefore, based on a previously presented musculoskeletal model [1] the dynamic pathways of the patella were computed. Then, the spatial motion was approximated by rheonomic polynomials and exploited for systematic evaluation of the MPFL length change patterns. Hence, 16 femoral attachment points at a radius of 5 mm and 10 mm around the radiographic centre point [2] were defined and the absolute length changes were recorded during deep knee flexion to 120 degree.

This approach allows for a systematic evaluation of numerous MPFL attachment sites while exploiting the physiological patella kinematics. The patella kinematics including shift, flexion, tilt and rotation as well as the MPFL length change patterns were consistent to in vitro and in vivo data in the literature [3–7] and therefore indicate validity of the numerical approach. The parameter study on the femoral attachment site should enable to determine the most isometric point and non-isometric variations corresponding to patellofemoral instability, arthritis or high graft load.

Keywords: biomechanics; patella kinematics; medial patellofemoral ligament (MPFL); attachment sites

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1 Introduction

Disorders of the musculoskeletal system become increasingly common, clinically relevant disorders of the patellofemoral joint (PFJ), which is the upper compartment of the knee joint and subject to high stress, are patellofemoral instability and arthritis with their pathogenesis related to biomechanical influencing factors [8]. For example, injuries of the capsular tissue can lead to patellar maltracking, pathological contact pressure in the patellofemoral slide-contact bearing and ultimately to luxation, which in turn can lead to additional severe injuries of the surrounding soft tissue. In order to give insight into the underlying failure mechanisms and evaluate treatment techniques, the understanding of the knee biomechanics is a key factor.

Whereas the dynamic pathway of the patella between 30 – 120 degree knee flexion is determined by the geometry of articulating cartilage surfaces, the dynamic positioning of the patella between 0 – 30 degree knee flexion is mainly stabilised by the surrounding soft tissue. Especially the medial patellofemoral ligament (MPFL) is a major stabiliser against lateral patella luxation in the range of 0 – 30 degree knee flexion.

Therefore, the femoral re fixation of the MPFL as treatment for patellar instability as well as habitual and traumatic patellar luxation has become increasingly popular [9–11]. Recent studies were focussed on the anatomy, surgical insertion points and reconstruction techniques of the MPFL, but there is still a lack of knowledge about the exact length change patterns for varying femoral attach-
ment sites during dynamic knee movement. Improper insertion point placement may lead to technical or clinical failures due to graft failure, degenerative joint changes or instability as biomechanical as well as clinical studies [12–16] revealed.

Figure 1: Sensor system definition according to van Kampen and Huiskes [3] for patella motion tracking relative to a femur-fixed reference.

The present study aims at the systematic evaluation of ligament insertion point placement corresponding to graft placement and graft tension by means of numerical simulation using multi-body models, which freed us from limitations going hand in hand with cadaver specimen or in vivo testing and allowed for detailed and reproducible analysis.

2 Material and methods

The previously presented musculoskeletal model of the patellofemoral joint [1] is based on CT-data from the standardised visible human dataset of a right lower extremity providing three dimensional, rigid bony and cartilage segment geometry. Therefore anatomical landmarks, coordinate frames and mass properties could be identified and exploited for multibody simulation.

The patellofemoral joint is implemented via a polygonal contact model with six degrees of freedom, whereas the tibiofemoral joint is modelled by a spatial four-bar linkage approximating the roll-glide movement of the knee.

Force elements according to Hill representing Mm. quadriceps femoris, semimembranosus, semitendinosus and biceps femoris actively generate muscle forces to drive the knee into flexion. The capsular tissue including the lateral and medial PFL was modelled by means of viscoelastic force elements, the Lig. patellae is represented via a rigid coupling element. Fan-shaped insertion of the MPFL was taken into account by implementing three portions inserting at 20% (proximal), 40% (central) and 60% (distal) of the patellar length at the patellar border, but solely at the radiographic insertion centre [2] at the femoral condyle. The deflection of the ligaments and tendons due to bony structures was considered by polygonal contact definition for LPFL, MPFL and M. quadriceps tendon.

2.1 Patella kinematics

The patella kinematics was evaluated with respect to a sensor system recommended by van Kampen and Huiskes [3], in which the patellar motion is described relatively to a femur-fixed reference frame (see Figure 1). In particular, a right-handed Cartesian reference frame $^f\Sigma’(x, y, z)$ was established in the highest point of the cartilage border in the femoral intercondylar notch with the coordinate axes $^f x$, $^f y$ and $^f z$ pointing medially, superiorly and anteriorly perpendicular to the sagittal, transversal and frontal plane, respectively. Accordingly, a coordinate frame $^p\Sigma’(p x, p y, p z)$ was established in the volumetric centre of the patella with the axes being aligned to the femoral system $^f\Sigma$ in full knee extension.

In order to systematically evaluate numerous model variations corresponding to varying femoral attachment sites of the MPFL, the forward dynamic six degree-of-freedom motion of the patella during deep knee flexion was recorded for the native knee (i.e. MPFL inserts at the radiographic centre of the femoral condyle) and approximated by sixth order polynomials to restore the patellar dynamics by means of a rheonomic joint. In this manner, patellar motion patterns were obtained as shift, flexion, tilt and rotation relative to the femur-fixed standard reference.
2.2 MPFL length change patterns at different femoral attachment sites

Based on the approximated patella kinematics, a parameter study on different femoral attachment sites of the MPFL was implemented in order to evaluate MPFL length change patterns giving comprehensive insight for MPFL reconstruction surgery.

Thereby, the femoral attachment site was systematically varied within a radius of 5 mm and 10 mm around the radiographic ideal position, i.e. 17 rheonomic model variations corresponding to the 17 attachment points were implemented (see Figure 2).

The MPFL portions span from the corresponding femoral attachment point to the patellar insertions points while being deflected by the bony condyle of the femur.

Note, all model variations exploit the obtained, approximated patella kinematics obtained from the native knee during deep knee flexion as mentioned above. This approach is considered to be valid, since the patella is mainly stabilised by the trochlear groove between 30–120 degree knee flexion (abnormal length change patterns rather cause an altered femoro-patellar contact pressure than altered patella kinematics). Moreover, the MPFL is reconstructed at 30 degree knee flexion to ensure entering of the trochlear groove.

3 Results

Patellar kinematics obtained from the forward dynamic musculoskeletal model could be approximated and was consistent with the kinematics obtained from cadaver and in vivo studies [3–5] as shown for patellar shift and flexion (Figure 3). Good agreement was found for the MPFL length change patterns obtained from our numerical simulation in comparison to the data available in the literature in Figure 4.

3.1 Patella kinematics

The patella shifted into lateral direction with increasing knee flexion. There was no noticeable medial shift between 0 and 30 degree. The patella flexion steadily increased from 0 degree at full knee extension to 80 degree at 120 degree knee flexion angle.

Figure 2: Multibody set-up for parameter study on MPFL length change patterns as a function of the femoral attachment point. The MPFL is fan-shaped inserting at three points along the medial patellar border and at one point at the femoral condyle. For the sake of clarity, only bony structures of femur, patella and tibia are shown.

3.2 MPFL length change patterns at different femoral attachment sites

In general, the length change varies greatly with the femoral insertion point. There were only minor differences in length change between the different patellar insertions. Thus, exclusively the central MPFL bundle is shown (Figure 4). Whilst there is almost isometry of the MPFL at flexion angles between 0 and 30 degree for the radiographic centre point, in particular the anterior-proximal and the posterior-distal insertions show severe non-isometry.

4 Discussion

Incorrect placement of the femoral refixation during medial patellofemoral ligament (MPFL) reconstruction surgery can lead to graft failure, degenerative joint changes as well as instability [12–16].

The present study examined the effect of varying femoral attachment sites of the MPFL after reconstruction surgery by means of a multibody model computing MPFL length change patterns during dynamic deep knee flexion. The described modelling technique is an approximation of the human knee by the multibody dynamics approach using discrete rigid bodies and force elements. Furthermore, the used visible human data set origins from only one human male. However, the results indicate validity of the numerical approach to the investigation of patella kinematics and therefore enabled us to systematically examine the influence of varying femoral attachments sites of the MPFL.
Figure 3: (a) patella shift and (b) patella flexion as a function of knee flexion angle in comparison to the literature [3–5]. Note, the coordinate conventions used in the literature slightly differ from the ones used in the present study recommended by [3], but still allow for being compared.

Briefly, the MPFL length change and the corresponding ligament tension revealed to be greatly affected by the femoral insertion. Therefore it is assumed that the increasing difference in MPFL length change patterns due to incorrectly placed refixation could lead to an increased femoro-patellar contact pressure at flexion angles from 30 – 120 degree and to patellofemoral instability at flexion angles from 0 – 30 degree, especially the anterior-proximal and the posterior-distal direction could cause severe problems. Moreover, a high elongation as it occurred for the anterior-proximal refixation may cause unexpectedly high graft tension and could lead to its technical failure. The MPFL fixed at the determined radiographic centre shows almost isometric behaviour until 30 degree and relaxes after the patella enters the trochlea.

In further studies, the influence of different patellar parameters in combination with varying femoral attachment sites will be examined.

Authors Statement
Conflict of interest: Authors state no conflict of interest.

Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors’ institutional review board or equivalent committee.

References


