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KNEE ARTHROPLASTY

Patella tracking and patella contact pressure in modular patellofemoral arthroplasty: a biomechanical in vitro analysis

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Abstract

Introduction In the recent years modular partial knee prosthesis with the opportunity to combine unicompartmental tibiofemoral (UKA) and patellofemoral prosthesis (PFJ) were introduced to the clinics. To date, little is known about the biomechanics of these bi-cruciate retaining prosthetic designs. Aim of this study was to evaluate the influence of a PFJ in bicompartmental arthroplasty (UKA + PFJ) on patella tracking and retropatella pressure distribution.

Methods A dynamic in vitro knee kinemator simulating an isokinetic extension cycle of the knee was used on eight knee specimen. Patella tracking and patellofemoral contact pressure were evaluated using pressure sensitive films after implantation of a medial UNI and after subsequent implantation of a PFJ.

Results Whereas the area contact pressure remained the same after PFJ implantation, the contact area was reduced significantly and significantly elevated peak pressures were determined in deep flexion and close to extension. The patella tracking was not significantly altered, however, effects of edge loading could be shown.

Conclusion When using PFJ prosthesis, one must be aware of altered pressure introduction on the retropatella surface compared to the physiological situation. The elevated peak pressures and reduced contact area may be an argument for patella resurfacing and the problems of edge loading indicate that care must be taken on the correct implantation of the device with no implant overhang.

Keywords Knee arthroplasty · Unicompartmental · Bicompartmental · Patellofemoral · Patella pressure

Introduction

The optimal treatment strategy for combined medial and patellofemoral osteoarthritis is still under discussion. Whereas some authors state that the patellofemoral osteoarthritis does not influence the outcome after medial unicompartmental knee replacement (UKA) [28], others suggest total (tricompartmental) knee replacement (TKA) for patients with symptomatic bicompartmental osteoarthritis [6].

In this context partial knee prosthesis with the opportunity to combine unicompartmental medial and patellofemoral prosthesis were introduced to the clinics as an alternative treatment strategy for named patients [26, 31]. These could be used as a primary bicompartmental replacement or in a staged concept for patients with remaining patellofemoral symptoms after medial replacement surgery. Even in mid- to long-term follow-up a high patient-satisfaction is reported [17].

However, little is known about the biomechanics of these modular bi-cruciate retaining prosthetic designs. Heyse et al. focused in their in vitro study on changes in the tibiofemoral kinematics and described an altered tibiofemoral contact point after patellofemoral replacement [16]. Similar to this, we found altered quadriceps extension forces after staged bicompartmental arthroplasty in a previous in vitro study [5]. However, the exact reason for

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these effects is not known and to date there is no data on the influence of the patellofemoral arthroplasty on the patella tracking, as well as its influence on retropatella pressure distribution. In TKA, several studies describe altered contact patterns and bearing surface forces at the patellofemoral joint [12, 19, 22, 23]. This is considered one important factor for remaining anterior knee pain after arthroplasty and especially attributed to paradoxical joint kinematics after resection of the anterior cruciate ligament or altered function of the posterior cruciate ligament. It could be shown, that a higher level of constrained in respect of a posterior stabilized system reduced patellofemoral contact pressure compared with posterior cruciate retaining TKA [2]. Hence our primary hypothesis was that a bi-cruciate retaining modular bicompartmental prosthesis would even result in a close to physiological pressure distribution.

Furthermore, recent designs in patellofemoral arthroplasty (PFJ) distinguished from its predecessors by the fact that they have become much smaller and are provided more as an inlay technique into the physiological trochlear. Especially this concept is meant not to alter the physiological patella biomechanics and tracking. However, to date there are no in vivo or in vitro studies evaluating these effects.

The objective of this study was to evaluate the influence of a patellofemoral replacement (PFJ) in staged bicompartmental arthroplasty (UKA + PFJ) on patella biomechanics. The patella tracking and changes in contact pressure were evaluated and compared to the native trochlea condition after isolated medial tibiofemoral replacement.

Methods

A dynamic knee kinemator simulating an isokinetic extension cycle of the knee close to the magnitude of the physiological forces and moments about the knee was used to evaluate patella tracking and patella contact pressure during motion. Eight fresh frozen adult knee specimen of nearly same size [mean age 74 (64–82) years, 5 male and 3 female] fulfilling the criteria of an intact skeleton and soft tissue envelop were used. The skin and subcutaneous tissue was removed and the femur and tibia were trimmed to a standard length of 25 cm from the joint line. The periarticular capsule, ligaments and musculature were preserved and the hamstring and quadriceps tendons were prepared. The tibial and femoral bone stumps were each embedded in a metal sleeve using bone cement so that the specimen could be mounted into the in vitro knee simulator with the femur fixed horizontally and the patella facing downwards (Fig. 1). This position was always marked and recorded to achieve an identical alignment for every test cycle. The tibia was attached to a swing arm using a mount with a linear rotational bearing that allows axial sliding and rotation of the tibia and motion in the varus/valgus plain. With this arrangement an isokinetic extension cycle from 120° knee flexion to full extension was simulated, as described earlier [8, 25, 30]. In brief, the tibia movement is provoked by the coordinated activation of three hydraulic cylinders. One was attached to the hamstring tendons that applied a constant 100 N flexion force during the whole extension cycle. The second was attached to the tibia swing arm with a constant counter force of 93 N to apply an external flexion moment. The third one was attached to the

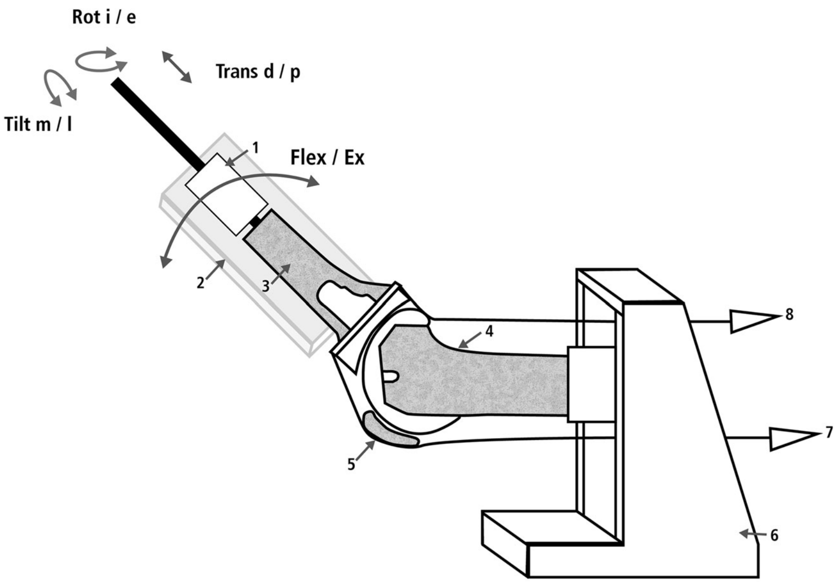

Fig. 1 An dynamic in vitro knee simulator, which can simulate muscular traction power using hydraulic cylinders, was used to simulate flexion/extension motion. *1* Force transducer tibial. *2* Tibia frame. *3* Tibia. *4* Femur. *5* Patella. *6* Femur frame. *7* Quadriceps force. *8* Hamstring force

quadriceps tendon to simulate quadriceps muscle force to extend the knee. This quadriceps force was adjusted in a closed-loop control cycle to generate a constant extension moment of 31 Nm about the knee. This results in a sinusoidal force profile ranging from 1800 N at 105° to 600 N at 10° to 20° of flexion. The degree of knee flexion was measured using an electronic goniometer attached to the tibial swing arm with a frequency of 10 Hz and an accuracy of ±0.05°.

The retropatellar pressure was analyzed using 33 × 22 mm electronic pressure sensitive films (K-Scan 4000, TekScan, Boston, USA). The films were preconditioned and calibrated as described earlier [2]. Before implantation 0.1 mm Teflon foils were glued on both sides of the sensor films to allow stable fixation onto the patella. This construct was sutured to the peripatella soft tissue so that the sensors were attached to the articular surface of the patella. By the use of the proprietary software (TekScan software v4.23, TekScan, Boston, USA) the area contact pressure (ACP), the peak contact pressure (PCP) as well as the contact area (mm^2) were recorded. With displaying the geometric center of the patella contact pressure in the coordinate system of the pressure films the patella tracking was evaluated.

Patellofemoral pressures were recorded in a first test cycle after isolated implantation of medial UNI and in a second test cycle after additional implantation of a PFJ prosthesis. At first, a fixed bearing medial unicompartmental knee replacement (Sigma® PFC High Performance Partial Knee; DePuy Orthopaedics, Warsaw, IN, USA) was implanted without bone cement according to the manufacturer's guidelines. The tibia base-plate was implanted according to the anatomical joint line and posterior tibial slope. The femoral component position was adjusted to the tibial component in flexion and extension. The patella was freed from osteophytes. Then, the pressure film was attached as described above. The knee capsule and soft tissues were readapted and the specimen was mounted in the simulator for said first test cycle.

The subsequent implantation of the trochlear component (Sigma® PFC High Performance Partial Knee Trochlear Component; DePuy Orthopaedics, Warsaw, IN, USA) was performed by the same surgical team according to the manufactures' protocol. The implant rotation was orientated on the physiological situation by the use of the transparent trial components. The intention was to achieve an alignment of the implant into the given trochlear and not to produce implant overhang or prominence (Inlay-technique). After implantation and closure of the capsule, the specimen was remounted in the simulator and the test cycles were repeated identically.

Mean, median and standard deviation values were evaluated using SPSS 20.0 (SPSS Inc., Chicago, IL). For statistical analysis, a paired sampled t test was used with a significance level of $p = 0.05$.

Results

The recorded mean area contact pressure (ACP), displayed in Fig. 2, represents the average load of the patella during the entire flexion/extension cycle. The native patellofemoral joint showed the typical curve with pressures at between 1.5 and 4 MPa. After implantation of PFJ prosthesis no significant differences in ACP were recorded ($p > 0.249$) with similar pressure curves for both scenarios (Fig. 2).

The evaluated peak contact pressure (PCP) during the test cycle, again, showed the typical curve profile of a native PFJ with maximum values of 9.41 MPa (SD 1.93) at 104° (Fig. 3). Now, after implantation of PFJ prosthesis a significant elevation of the peak pressure was detected for deep flexion to a maximum of 12.01 MPa (SD 3.45, $p = 0.043$). During the mid-flexion-range of motion (90°–40° flexion) both curves had similar characteristics with no statistical difference ($p > 0.249$). At between 30° and 20° degrees of flexion a second retropatellar pressure peak could be detected after implantation of PFJ prosthesis, that was not likely in the native situation. However, this difference was not of statistical significance ($p = 0.07$).

In Fig. 4 the articulating contact area of the patella with the trochlea over the entire flexion/extension cycle is displayed. The difference between the native situation and after prosthetic reconstruction of the trochlea was of statistical significance at between 120° and 40° of flexion ($p < 0.05$).

Evaluating the center of the patella contact pressure detected on the pressure films the patella tracking is reconstructed as displayed in Fig. 5. This illustration indicates that after implantation of a PFJ prosthesis the patella articulation is medialized compared to the native condition by about 2.27 mm (SD 1.36). Initially a proximalisation of the contact center of the patella can be detected by about 0.88 mm. From 100° of flexion to full extension a distalisation of the

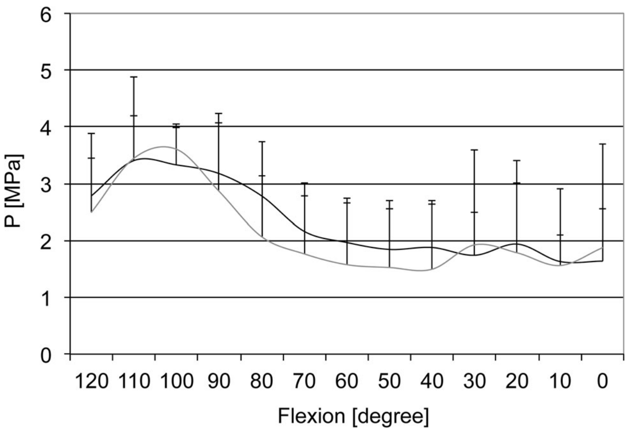

Fig. 2 Patellofemoral area contact pressure in the native patellofemoral joint (*black*) and after implantation of a PFJ prosthesis (*grey*) from 120° knee flexion to full extension. *Error bars* representing the standard deviation (SD)

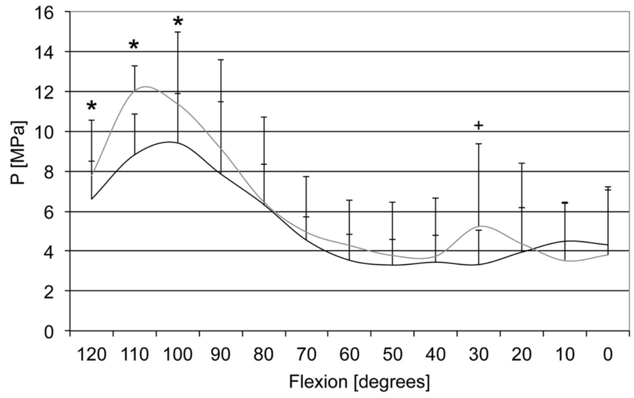

Fig. 3 Patellofemoral peak contact pressure in the native patellofemoral joint (*black*) and after implantation of a PFJ prosthesis (*grey*) from 120° knee flexion to full extension. $^{*}p < 0.05$; $^{+}p = 0.07$, *error bars* representing the SD

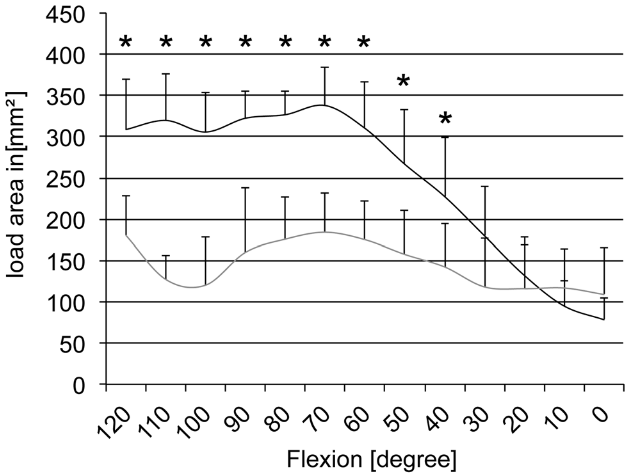

Fig. 4 Patellofemoral load area in the native patellofemoral joint (*black*) and after implantation of a PFJ prosthesis (*grey*) from 120° knee flexion to full extension. $^{*}p < 0.05$, *error bars* representing the SD

articulation by 1.07 mm (SD 1.27) is apparent. While both tracking pattern of the native and reconstructed scenario are similar, especially in full extension the contact area of the patella to the trochlea is altered to a more distal and more medial center of articulation.

Discussion

The scope of this study was to evaluate the biomechanical effects of implanting a trochlea prosthesis in a concept of modular bi-cruciate retaining knee arthroplasty regarding the effect on the retropatellar pressure introduction and patella tracking.

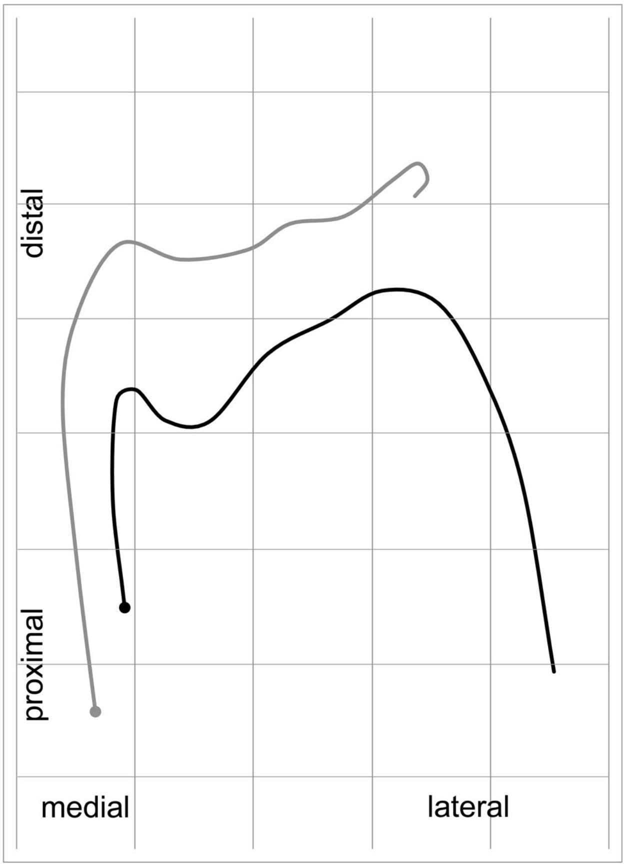

Fig. 5 Mean position of the center of patellar contact pressure in the native condition (*black*) and after implantation of PFJ prosthesis (*grey*) from 120° knee flexion to full extension. The highlighted *full stop* represents the starting point at 120° flexion. The raster corresponds to 5 mm increments

The most important finding was that there was no significant change in the overall patellofemoral area contact pressure after implantation of the trochlea resurfacing component compared to the native trochlea. This generally supports our hypothesis that a bi-cruciate retaining modular prosthesis with the preservation of the physiological leverarm and femoral rollback would result in a close to physiological pressure introduction to the patella. This is in contrast to data published on cruciate retaining TKA [2, 12, 15, 20, 30]. Here a significant elevation of the area contact pressure was shown before, utilizing the same or different in vitro test setups.

Typically, the physiological patella articulation in vivo shows contact pressures at between 1.3 and 4 MPa during knee motion with maximum values in deep flexion. Depending on special activities and motions patellofemoral pressure peaks from about 13.8 MPa have been calculated [1]. The patellofemoral area contact pressures determined in this study were in this range.

The second most important finding was, that even though the overall patellofemoral pressure remained about the same, there was a significant elevation of the retropatellar peak pressure after implantation of a PFJ prosthesis compared to the native situation, especially in deep flexion. A second peak was observed in extension when the patella reaches the proximal end of the implant. In the literature, an elevation of the patellofemoral peak pressure is also reported for TKA [2, 10, 12, 15, 20, 27, 29, 30]. However, those very high peaks as seen in this study are uncommon for tricompartmental prosthesis. As they occurred in the very deep flexion, where the implant is very small and not about covering the whole articulation to the patella, as well as close to full extension, where the patella might ride on the very top of the implant, we put these findings to the specific design of the implant. An edge loading on the implant is likely to explain these effects. In this context, Lonner et al. defined the design of the proximal extension of the anterior flange, as well as the distal tip and sagittal radius as the crucial elements in the prosthetic design of PFJ because edge loading can occur at these sites [21]. In a clinical study comparing inlay versus onlay-style designs in patellofemoral arthroplasty Feucht et al. reported a higher incidence of progressive tibiofemoral arthritis with the onlay trochlea prosthesis [9]. However, the actual reason for this remained unclear, they put these findings to altered patella kinematics and potential inflammation due to mechanical stress. Equal effects were for example reported for inlay implants at the tibiofemoral joint, where even mild implant overhang at the cartilage surface resulted in high pressure peaks [3].

At third we found the articulating surface area between patella and trochlea significantly reduced after implantation of a trochlea component. Whereas in the native situation almost the whole retropatellar surface engages with the trochlea during deep and midflexion, in the resurfaced situation this contact area was concentrated to a small area of 150 mm^2 in average. This was true for the whole range of motion. This finding perfectly fits to the elevated peak pressure, while the area contact pressure remains the same. Equal effects were also reported for TKA before [10, 11, 22].

Lastly, the analysis of the center of patellar pressure motion showed equal patella tracking pattern for both native and resurfaced trochlea. Earlier studies conducted with an ultrasound based three-dimensional motion analysis system in the same test setup affirmed a good correlation of the center of patella pressure motion with the actual patella motion [23, 24]. Both situations showed a typical curve with the center of mean patella pressure moving laterally and proximally during the extension cycle. The shown difference in the very extension situation can again be attributed to the prosthetic design and a methodological error. The pressure peak remains on the very distal end of the patella, where the top of the implant still engages with the patella, whereas in the native condition there is a contact to the femoral cortex in the proximal region of the patella. Equally, the initial proximalisation of the articulation area can be explained by an early engagement with the distal tip of the implant in deep flexion. This again is in line with the findings of elevated peak pressure in deep flexion and close to extension. Equal effects on altered patella tracking have been documented in similar in vitro studies with TKA [2, 23]. However, this data indicates that close attention must be paid to prevent femoral overstuffing or overhang especially at the top end of the trochlea.

As this is an in vitro study, several limitations need to be discussed. At first, our setup only simulates one constant extension moment during the whole extension cycle from 120° of flexion to full extension. This distinguishes the experimental setup from the factual varying peak extension moments in vivo as during squatting or gait, for example [14]. This constant extension moment was set to 31 Nm, which represents the mean extension moment reached by patients over a isokinetic extension cycle [25]. The counterforce of the hamstrings was set to 100 Nm, which is according to Durselen et al.'s analysis about the physiological muscle co-contraction force around the knee [7]. This co-contraction is meant to achieve an additional and close to natural stabilization of the knee joint for the in vitro setting. As both are simplified models of complex in vivo motion, the quantitative results of the in vitro study should not be translated directly to in vivo conditions. Complex movements like gait or squatting cannot be assessed with this setup. However, the methodology is suitable to illustrate the biomechanical effect after implantation of a trochlea prosthesis for both in vitro and in vivo and was used and validated in many equal studies, before.

Second, area and peak contact pressures were determined by an electronic pressure sensitive sensor. This identical setup was also used and verified in several studies, before [3, 13, 24]. As reported earlier, limitations of the sensor include the thickness (0.1 mm), its sensitivity to temperature changes, its disposition for crinkling and the establishment of the position [4]. As all test cycles on one specimen were performed on 1 day and care was taken not to change the position of the folia that was glued and sutured to the back of the patella, we tried to minimize said limitations. That was also the reason that no retropatellar resurfacing was performed in this study, as this would have lead to an uncontrollable position change of the pressure sensor and the data reliability would have been altered.

To put our findings into a clinical context, low patellofemoral pressure after knee arthroplasty are considered to be advantageous as high pressures might be accountable for postoperative anterior knee pain [10, 16, 23, 29, 30]. Especially the reported pressure concentration and the peaks at the very implant edges might represent a clinical problem [21]. So care must be taken regarding a perfect implantation technique with no implant overhang at the distal point and no anterior femoral overstuffing. Similar negative biomechanical effects of overstuffing have also recently been reported on UKA [18].

In summary, when using PFJ prosthesis, one must be aware of altered pressure introduction on the retropatella surface compared to the physiological situation. Our primary hypothesis that the patella tracking as well as the patellofemoral contact pressure is not significant altered after implantation of a trochlea device in the context of modular bicompartmental arthroplasty of the knee is fulfilled. However, we were able to determine significant changes in the patellofemoral contact area and the peak pressures occurring, especially at the transition between implant and cartilage. This is special for the trochlea prosthesis, as there is not only engagement between two prosthetic components but also with native structures. This indicates that care must be taken to carefully integrate such devices in the surrounding structures.

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