Using a patella reduced technique while balancing a TKA results in restored physiological strain in the collateral ligaments: An ex vivo kinematic analysis

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All listed authors have contributed to the study design, acquisition, analysis, and interpretation of the data. Moreover, all authors have reviewed, and confirmed the accuracy of the whole text and approved the final manuscript.

Conflicts of interest/Competing interests

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Abstract

Introduction

Poor soft tissue balance in total knee arthroplasty (TKA) often results in patient dissatisfaction and reduced joint longevity. Patella-in-Place balancing (PIPB) is a novel technique which aims to restore native collateral ligament behavior without collateral ligament release, while restoring postoperative patellar position. This study aimed to assess the effectiveness of this novel technique through a detailed ex vivo biomechanical analysis by comparing post-TKA tibiofemoral kinematics and collateral ligament behavior to the native condition.

Materials and Methods

Eight fresh-frozen cadaveric legs (89.2±6 yrs) were tested on a validated dynamic knee simulator, following computed tomography imaging. Specimens were subjected to passive flexion (10° – 120°), squatting (35° – 100°) and varus/valgus laxity testing (10 Nm at 0°, 30°, 60°, 90° flexion). An optical motion capture system recorded markers affixed rigidly to the femur, tibia and patella, while digital extensometers longitudinally affixed to the superficial medial collateral ligament (MCL) and lateral collateral ligament (LCL) collected synchronized strain data. Following native testing, a Stryker Triathlon CR TKA (Stryker, MI, USA) was performed on each specimen and the identical testing protocol was repeated. Statistical analyses were performed using a linear mixed model for functional motor tasks, while Wilcoxon signed-rank test was used for laxity tests ($p<0.05$).

Results

Postoperative laxity was lower than the native condition at all flexion angles while postoperative ligament strain was lowered only for MCL at 30° ($p=0.017$) and 60° ($p=0.011$). Postoperative femoral rollback patterns were comparable to the native condition in passive flexion but demonstrated a more pronounced medial pivot during squatting.

Conclusions

Balancing a TKA with the PIPB technique resulted in reduced joint laxity, while restoring collateral ligament strains. The technique also seemed to restore kinematics and strains, especially in passive flexion.

Keywords: total knee arthroplasty, ligament balancing, patella in place balancing, ligament laxity, collateral ligament strain.

Introduction

Orthopedic surgeons can choose from a large variety of total knee arthroplasty (TKA) designs. Regardless of choice, patient satisfaction rates generally do not exceed 80% [1–5]. Recent improvements in the associated surgical technique specifically aim to improve post-arthroplasty alignment through better instrumentation and computer-assistance [6–8]. The literature indicates this indeed results in a decrease of alignment outliers as compared to conventional techniques [7]. Some knee surgeons have herewith emphasized that a good outcome in primary TKA is more dependent on soft-tissue management than bone management. A correct soft tissue balance indeed constitutes a very important factor for patient satisfaction [9, 10]. However, thus far improved soft tissue balancing techniques with all kinds of balancers and/or tensioners have not been able to provide reproducible results in the hands of orthopedic surgeons [11]. Patients often complain that their operated knee does not feel ‘normal’, potentially due to a disruption of the proprioceptive mechanism of the knee, which may explain the persistence of postoperative dissatisfaction [12]. This feeling might be a consequence of a small malalignment caused by the preservation of the periarticular soft tissues. Conversely, conventional alignment targets may achieve mechanically-sound bony alignment while ignoring the soft tissue envelope. Indeed, mechanically aligned positioning of TKA components frequently generates technically uncorrectable collateral ligament imbalance [13].

On the other hand, no consensus currently exists on which surgical technique results in an optimal balanced TKA. The optimal "target" soft tissue balance for each patient undergoing total knee arthroplasty (TKA) thus remains unknown [14–16]. Many surgeons believe that progressive shortening or contraction of the soft tissue structures on the medial side should be targeted, whereas the lateral structures are allowed to become stretched [17, 18]. Furthermore, since the TKA is an artificial joint with other material properties than the native knee and absence of the meniscus, less laxity might be more suitable. We think that the optimal balanced knee should have little or no ligamentous slack post-operatively to compensate absence of the meniscus. From a technical standpoint, obtaining a balanced and symmetric flexion/extension gap during TKA is challenging to achieve intraoperatively and, importantly, often requires soft tissue release and repeated bone resection [19]. As outlined above, it can be argued that releasing should be prevented as it likely impedes proprioception [20] and delicate sensorial function in many patients [21–23]. Furthermore, orthopedic surgeons are convinced of the relative ease in intraoperatively assessing coronal balance by feel and look in extension; however, many studies have demonstrated the opposite and thus can result in variable and inconsistent results [24, 25]. In a study by McAuliffe et al. the ‘classic’ pattern of contracted medial tissue and lax lateral tissue was only recorded in 6.4% (5/78) of patients [17]. One could argue, achieving an optimal balance between stability and mobility thus requires an accurate pre-operative planning with specific focus on an optimal balancing of the soft tissues, followed by an accurate execution. Unfortunately, current commercially available pre-operative planning tools primarily support the surgeon in obtaining mechanical alignment and therewith do not integrate soft tissue balancing. Furthermore, planning is performed on static models that provide detailed anatomical information but no functional information [26]. Finally, recent developments in sensor and robotic technologies claim to provide surgeons with the ability to quantitatively measure soft tissue loads, tension and gap balance intraoperatively throughout the range of motion of the knee [27]. Besides the fact that the literature raised some concerns in terms of the reliability of pressure sensing devices and the measurements are typically obtained only after the cuts are made with the patella in a non-physiological dislocated position [28, 29].

Nevertheless the position of the patella (everted, laterally retracted or in situ) has been shown to have an important influence on the measurements of soft tissue balance [30] with effect on the medio-lateral distribution of tibiofemoral contact forces [31–33]. Keeping the patella in reduced position is thus clearly important during gap balancing. The novel surgical technique—Patella-in-Place balancing (PIPB)—~~-~~described in this study specifically aims to balance the flexion gap with the patella reduced without soft tissue releases.

~~-~~In recent years, t~~his technique~~he PIPB technique ~~-~~has been performed in over 3000 patients [34]. Moreover, patient-records collected through 10 years of follow-up since 2007 following PIPB, which will be soon published, seem to indicate [illegible] Therefore, this study aimed to assess the effectiveness of this novel technique through a detailed *ex vivo* biomechanical analysis by comparing post-TKA tibiofemoral kinematics and collateral ligament behavior to the native condition .

It is hypothesized that when using the PIPB, (1) the post-operative laxity in valgus and varus would be smaller than in the native situation of the same knee and (2) post-operative kinematics would be close to the native kinematics especially for femoral rollback.

Materials and Methods

Eight fresh-frozen full cadaveric legs (female (2 unilateral, right and left), male (3 bilateral), (89.2±6 yr)) were obtained following ethical approval (H019 2015-11-04). Bi-cortical bone pins were inserted into the femur, tibia, and patella in order to attach rigid frames containing reflective spheres. Computed tomography (CT) scans

(Siemens Somatom Definition Flash, Erlangen, Germany) were acquired from all specimens in full extension with a 0.75 mm slice thickness. Segmentation software (Mimics 19.0, Materialise, Leuven, Belgium) was used to identify the location of the spherical markers and specific anatomic landmarks from CT images [35]. These landmarks were used to define a joint coordinate system for the femur and tibia based on the Grood and Suntay convention [36].

Specimens were thawed twenty-four hours prior to testing and the femur and tibia were resected 320 mm proximally and 280 mm distally from the knee joint line , respectively. The skin and subcutaneous tissue surrounding the knee complex were carefully removed in order to preserve the capsule, ligaments, and tendons. Suture loops were passed through the medial/lateral hamstring tendons and the quadriceps tendon was fixed using a custom-made clamp. The femur and tibia were embedded into metal containers using acrylic resin (Struers, Ballerup, Denmark), while femur was kept in approximately 6° of valgus. Calibrated axial extensometers (accuracy = 0.5%, MTS, Type 634.12F-24, Eden Prairie, Minnesota, USA) were attached to the superficial medial collateral ligament (MCL) and the lateral collateral ligament (LCL) -along the longitudinal axis of the ligaments around the mid-portion region- using a series of suture loops (/0 non-absorbable polyester braided suture wire; Cardioxyl, Peters Surgical, Bobigny Cedex, France) while the knee was held in its neutral position Moreover, the attachment of the extensometers was performed with the knee unloaded and in full extension.

The specimens were mounted in a dynamic knee simulator system that provides the knee joint with all six degrees of freedom (Fig.1a). More precisely, the hip joint interface can rotate in the sagittal plane and translate up, and down, allowing flexion and extension. Furthermore, the ankle joint has three rotational degrees of freedom allowing internal-external rotation, abduction-adduction and flexion-extension as well as medial-lateral translation. As such, our set-up only controls the flexion angle of the knee as a function of time, while all other kinematic degrees of freedom of the knee joint were left free~~kinematic rig (Fig.1a), the details of which have been previously described~~ [37].~~, and~~

The native specimens were subjected to two main functional motions and a laxity test: passive flexion (10° – 120°), varus/valgus laxity testing and squatting (35° – 100°). During passive flexion, the femur container was kept rigidly fixed to the knee rig while the tibia and quadriceps tendon were left unconstrained. The specimen was then manually cycled through its maximum flexion range. For the varus/valgus laxity test, a handheld digital dynamometer (0.1 N resolution; Series 4, Mark-10, Copiague, USA) was used to produce a resultant moment of 10 Nm, which has been previously reported to be below the MCL/LCL damage threshold [38, 39]. Therethrough, a tensile force was manually applied at the distal tibia (approximate location of the medial/lateral malleolus), perpendicular to the tibial longitudinal axis. Real-time kinematics feedback was used to accurately perform the varus/valgus laxity tests at 0°, 30°, 60° and 90° of flexion angle. During squatting, 50 N constant force springs were attached to the medial and lateral hamstrings in order to apply a constant load throughout the full flexion cycle, while the quadriceps clamp was connected to a linear actuator. The force of the electromechanical quadriceps actuator was computer controlled to apply physiological quadriceps load while maintaining a vertical ankle load of 110 N during squatting. During all trials, the trajectories of the retro-reflective spheres attached to the specimens were recorded using six infrared cameras (MX40+, Vicon Motion Systems, Oxford, UK) operating at 100 Hz. Additionally, Vicon~~data from the~~ motion capture cameras~~,~~, the digital dynamometer (200 Hz) and extensometers (200 Hz) ~~data~~ were all synchronously acquired through a custom Labview program (v2015, National Instruments, Austin, Texas, USA) and the data acquisition platform (CompactDAQ, National Instruments, Austin, Texas, USA) based on digital trigger signals from the motion capture system. E~~ while e~~ach specimen underwent passive flexion, varus/valgus laxity, and squatting in triplicate.

Surgical Technique

This surgical technique is based on custom designed patella in place balancer which requires a tibia first, technique with the patella in its anatomical position and preservation of the posterior cruciate ligament (PCL), without any collateral ligament or lateral patellar retinaculum releases. The tibia first technique was started with the knee in 90° flexion. Before performing the tibial cut, all the femoral osteophytes (including the posterior osteophytes) were removed. The height of the tibial resection was defined in function of the tibial insertion of the PCL or the medial synovial membrane insertion. Natural tibial slope was respected. A tibial baseplate was the fixed on the resected surface.

Positioning of the patella in place balancing system

An intramedullary rod was placed in the femoral canal and the Transcondylar pin drill guide (TCDG) was put on the direction instrument (Fig.1b-c). The upper part of the guide was then placed at the level of the lateral femoral condyle. The drill guide was fixed at the medial upper part of the first guide. This drill guide was placed laterally in such a way that the drill hole started at the lateral border of the trochlea and exits at a point just anterior and medial to the center of the posterior condyle. The length of the threaded pin was found at the arm of the drill guide. Drilling was performed with a 3.2 size drill. The size of the lateral pin was carefully chosen to avoid substantial protrusion above the trochlea to allow patella reduction. To drill the medial pin, similar positioning was used on the medial femoral condyle. Next, the knee was maximally flexed to allow to attach the special keeper on each threaded pin. (Fig.1d.). Subsequently, we reduced the patella in extension and brought the knee back into 90° of flexion while applying force to place the keepers on the tibial baseplate and maintain the patella in its natural position.

Adjusting the length of the collateral ligaments using PIPB

While in flexion, the proximal tibia was pushed as far posteriorly as possible to counteract the absence of the ACL and to avoid verticalizing the PCL. By then rotating the pins with the hexagonal screwdriver (Fig. 1e) we adjusted the length of the ligaments (i.e. the soft tissue envelope) and after removing the slack aimed at restoring their physiological tension [40, 41]. We alternately lenghtened the lateral and medial pin until an end stop feeling appeared. Following, the surgeon performed a varus/valgus test in 90° to test if stability was successfully obtained. If not, further adjustments were made by turning the pins [24, 31, 42, 43]. No complications or adverse events were observed by the surgeons while using the transcondylar pins during the surgical interventions.

The next step was to measure the height of the induced flexion gap which was subsequently copied to the extension gap since our technique relies on isometry of the collateral ligaments. Hereupon, the classical sequence of surgical steps were followed to perform a Stryker Triathlon CR TKA (Stryker, MI, USA), while the femoral component was uncemented and the tibial component was cemented. Following TKA, all kinematic trials were repeated using identical methods as explained in the above sections.

Data Processing

Tibiofemoral translations/rotations during motion tasks were computed using dedicated motion capture software (Nexus 2.9, Vicon, Oxford, UK) and custom-written code in Matlab (R2018b, Mathworks Inc, Natick, MA, USA) by using the recorded marker trajectories [35, 36]. For passive flexion and squatting, each kinematic variable was down sampled and interpolated at intervals of 1° of flexion and within a common range of knee flexion shared by all specimens. Following, the extensometer and digital dynamometer data were cropped based on the collected digital trigger signals. This process allowed us to match all the data at dedicated time stamps. ~~In addition to this~~Furthermore, the absolute difference between the rested (e.g. no load) and loaded state was used to determine the net amount of varus/valgus laxity and change in engineering strain of MCL/LCL for the laxity tests; i.e. the strain at the start of the trial is considered to be 0% and all subsequent measurements were expressed relative to this initial value.

Statistical Analysis

To allow comparisons between collected kinematic trials, all data were averaged across the specimens. In order to ~~compare~~ analyze~~the statistical~~ difference between pre- and post-op during passive flexion and squatting~~conditions~~, a linear mixed model was used without application of transformations in case of non-normality residuals ~~was used~~ [44–46]. To compare pre- to post-op differences during laxity testing, we used a non-parametric Wilcoxon Signed Rank test in view of the small sample size ~~.~~and non-normally distributions of certain parameters. ~~The difference in ligament strain and joint laxity was compared using Wilcoxon Signed Rank Test due to sample size and/or non-normality of the data.~~ All statistical analyses were performed in R (R-Studio Version 1.0.143, Boston, MA) and the significance level was determined at p<0.05.

Results

Laxity Testing

TKA demonstrated smaller varus and valgus laxity with respect to the native condition (Fig. 2). The varus laxity of TKA was significantly reduced compared to the native condition at both 0° ((Native, mean: 2.9°, 95% confidence interval [CI]: 2.1°-3.7°), (TKA, mean: 2°, CI: 1.1°-2.9°), p=0.025) and 90° ((Native, mean: 3.1°, CI: 2.3°-4°), (TKA, mean: 2°, CI: 1.2°-2.9°), p=0.017)) of flexion. Likewise, the valgus laxity following TKA was significantly reduced with respect to the native condition at 30° ((Native, mean: 3.7°, CI: 2.9°-4.5°), (TKA, mean: 2.1°, CI: 1.5°-2.8°), p=0.017)), 60° ((Native, mean: 5.3°, CI: 4.3°-6.5°), (TKA, mean: 2.2°, CI: 1.5°-2.8°), p=0.011)) and 90° ((Native, mean: 3.7°, CI: 2.9°-4.5°), (TKA, mean: 2.1°, CI: 1.4°-3°), p=0.011)) of flexion.

Although, LCL strain of TKA was in general reduced compared to the native condition at each flexion position (Fig. 3), no significant differences were found (p>0.069). Contrary, MCL strain of both conditions were significantly reduced throughout mid-flexion: 30° ((Native, mean: 2.9%, CI: 2.2%-3.5%), (TKA, mean: 2%, CI: 1%-3%), p=0.017)) and 60° ((Native, mean: 2.7%, CI: 2%-3.2%), (TKA, mean: 1.8%, CI: 1%-2.6%), p=0.011)).

Functional motions

Although native and TKA conditions were comparable in terms of varus/valgus orientation throughout passive flexion-extension (Fig. 4a), TKA demonstrated significantly increased varus compared to the native (65° - 120°, p<0.045). Both native and TKA demonstrated increasing tibial internal rotation with increasing flexion (Fig.4b), although for TKA this increase in rotation was significantly reduced compared to the native condition beyond mid-flexion, (67° - 120°, p <0.046). On the other hand, the MCL (relative change) in both TKA and the native conditions demonstrated increasing negative strain,i.e. length shortening or relaxation, with progressive knee flexion. Moreover, TKA demonstrated significantly increased MCL relaxation in TKA condition (Fig. 4c) in deep flexion (82° - 120°, p <0.049). Similar relaxation behavior was observed with increasing flexion in the LCL in both the native and TKA conditions. Nevertheless, LCL strain relaxation following TKA was significantly less pronounced with respect to the native condition (Fig. 4d) between 42°and 58° of flexion (p <0.048).

During squatting, the post-TKA condition was, similar to passive flexion, found to be in significant ~~in significant~~ more varus with respect to the native condition (Fig. 4e), (35° - 100°, p<0.014). However, tibial internal rotation of TKA during squatting (Fig. 4f) was only significantly different from native until deep flexion (35° - 91°, p<0.049). Again similar to passive flexion-extension motion, TKA demonstrated higher MCL strain during squatting from mid-flexion onwards (Fig. 4g), (55° - 100°, p<0.046), and reduced LCL strain in the mid-flexion range (Fig. 4h), (60° - 82°, p<0.046).

In terms of translational behaviour during passive flexion, the lateral (10° - 63°, <0.041) and medial (10° - 120°, <0.046) antero-posterior translation following TKA (Fig. 5) were found to be significantly different than the native condition. Nevertheless, both native and TKA presented medial pivoting motion, which can also be observed from the tibial internal rotation graph (Fig. 4b). During squatting, TKA exhibited larger lateral translation and reduced medial translation compared to the native. As such, both native and TKA presented significantly different ranges of motion for both the medial (35° - 78°, <0.049) and lateral (35° - 76°, p <0.4.9) antero-posterior translations until mid-flexion. Accordingly, TKA thus demonstrated a more pronounced screw-home mechanism during squatting compared to native (Fig. 5 and Fig. 4f).

In terms of patellar kinematics during squatting, patellar flexion (Fig. 6a) demonstrated a very comparable steep linear increase in both native and TKA and as a result no significant difference was found (p>0.56). On the other hand, in terms of post-operative patellar abduction (Fig. 6b) both conditions demonstrated opposite behavior (53° - 100°, p<0.045), despite the apparent restoration of the abduction angle at early flexion. Although both pre-and post-op conditions demonstrated an external tilted patella (Fig 6c), TKA demonstrated significantly increased internal rotation from early flexion onwards (35° - 86°, $p<0.032$) which reduced from flexion to extension. In addition, TKA demonstrated a posterior and inferior offset in terms of antero-posterior (Fig. 6d, 35° - 100°, $p<0.001$) and infero-superior (Fig. 6e, 41° - 86°, $p<0.047$) translations during squatting. However, for medio-lateral translation (Fig. 6f), both native and TKA conditions were very comparable throughout knee flexion and no significant difference was observed ($p>0.62$).

Discussion

The present study assessed the effectiveness of a novel patella in place balancing (PIPB) device through a detailed *ex vivo* biomechanical analysis by comparing post single radius TKA tibiofemoral kinematics and collateral ligament behavior to the native condition.

With regards to our primary hypothesis, i.e., the post-operative laxity in valgus and varus would be smaller than in the native situation when using the PIPB, the main finding of this study was that laxity was reduced for TKA compared to the native condition at all flexion angles during adduction and abduction laxity tests. Moreover, TKA exhibited similar and no significantly different collateral strains with respect to the native condition, except for MCL in mid-flexion range. On the other hand, the largest strain differences were found after early flexion and in mid-flexion range for MCL and LCL during laxity test, respectively. This trend was also observed in LCL in passive flexion and squatting; however, MCL strain exhibited opposite relation in both conditions. With regard to our secondary hypothesis, i.e. that post-operative kinematics would be close to the native kinematics especially for femoral rollback, the femoral rollback pattern of TKA indeed demonstrated a similar kinematic trend as compared to the native condition. Nevertheless, for passive flexion, the translations in both the medial and lateral regions during passive flexion and squatting motions were statistically different and thus rejected our second hypothesis.

One of the specific surgical goals of the PIPB-technique is to remove slackness in the collateral ligaments while ensuring isometry throughout flexion. As such, our results clearly show that the slackness in both MCL and LCL following TKA were indeed removed, as demonstrated by the linear behavior from zero to 10 Nm without any toe-region in strain (Fig. 3). Furthermore, the observed strain patterns were all very comparable at all flexion angles tested following TKA, indirectly indicating that the intended isometry throughout flexion of both ligaments was achieved during laxity testing.

As mentioned, our results post-TKA demonstrated a clear femoral rollback pattern, i.e. a medial pivoting movement, associated with increased tibial internal rotation in passive flexion, while maintaining similar patterns in terms of MCL and LCL strain as compared to the native knee. Interestingly, the post-TKA rollback pattern during squatting was more pronounced compared to native due to increased tibial internal rotation and associated with greater MCL strain and isometric behavior of the LCL. This greater lateral translation for TKA during squatting seems to be associated with the larger differences observed between native and TKA in valgus laxity as compared to changes in varus laxity. First, it should be noted that this difference in both kinematics and strain may be a direct consequence of the specific implant design, since no implant is currently able to fully mimic the specific articular geometry of the patient. Additionally, the loss of menisci likely contributed to these difference compared to the native condition.. Finally, our finding of larger differences in valgus as compared to varus laxity corresponds with the study of Baier et al. who reported that the post-operative kinematics should be closer to the native kinematics, especially for the rollback of the lateral condyle in order to maintain natural kinematics [47], which also agreed with our findings in terms of femoral rollback on the tibia (Fig. 5). Since the joint surface has been replaced with metal and a polyethylene insert, which is known to be stiffer compared to cartilage, one surgically aims for less post-operative laxity in valgus to ensure medial-pivoting motion.

The PIPB technique specifically aims to prevent patella eversion during the intra-operative assessment. Likely this contributed to the fact that we found clear associations between pre-to-post-TKA tibiofemoral and patellofemoral kinematic differences during squatting. As the tibia internally rotated, the patella tended to tilt medially for TKA, while the native condition exhibited more neutral orientation in both. Moreover, since TKA demonstrated increased varus (Fig. 4e), the patella seemed to medially rotate (valgus) to preserve the line of action of the extensor mechanism, as can indeed be seen in Fig 6b.

Additionally, intraoperative patellar positioning has been reported to have a strong influence on the intra-operative assessment of the joint gap; where patellar eversion is known to decrease the lateral joint gap more than the medial joint gap, both in knee extension and flexion [48]. Cadaveric studies by Luring et al. have further confirmed that patellar eversion thus causes increased valgus during soft tissue balancing in TKA [32], which corresponds with our finding of reduced valgus/increased varus compared to native during both squatting and passive flexion obtained with the patella-in-place technique assessed in this study. Finally, trying to balance the tibiofemoral flexion gap with the patella in everted or subluxed position has been reported to influence tibial rotation in flexion and strain in the collateral ligaments [32, 33, 49], and thus likely played a role in our finding in terms of these specific biomechanical parameters.

Interestingly, the varus/valgus laxity testing in our study demonstrated similar symmetrical behavior of the medial and lateral balance in both extension and flexion post-operatively, which is a specific target of the PIPB technique. This finding also extends to the comparable strains in the MCL and LCL, which has been reported to be an important factor in terms of patient satisfaction [1, 2, 15, 41, 50–55].

More in general, proper soft tissue balance is indeed commonly accepted to be vital for post-operative outcome as it leads to stability, and longer implant survival [9]. Nevertheless, there is still much debate on the exact definition of an optimally balanced TKA and consequently no gold standard currently exists [56, 57]. However, Babazadeh et al. defined a balanced knee joint as: a full range of flexion-extension motion, symmetrical medial/lateral balance at both full extension and 90° of flexion, correct varus/valgus alignment in flexion/extension, a well tracking patella during full motion, without excessive rollback of the femur on the tibia and correct rotational balance between the tibial and femoral components [58]. Similarly, Lee et al. suggested that rectangular-shaped joint gap in extension and 90° of flexion is a goal for proper soft tissue balancing [59]. Their study indicated that the suggested gap offers restored function of the knee joint and may provide a proper contact pressure, while maintaining tibiofemoral kinematics [59]. Considering aforementioned definitions, our results show that the PIPB technique provides a full range of flexion motion; it must be noted, however, that the range of the motion was set to 10°-120° for passive flexion and 35°-100° for squatting. Symmetrical medial/lateral balance was observed in complete extension and 90° flexion (Fig. 2), with correct varus/valgus alignment in extension (Fig. 4a). Postoperative patellar kinematics reflected the native condition over the complete range of motion with only small offsets and similar patterns in patellar translation (Fig. 6d-f). In the case of femoral rollback on the tibia, postoperative results conformed well with the native pattern, despite slightly reduced rollback medially and increased rollback laterally. Moreover, the screw-home mechanism was successfully restored with appropriate rotational balance between the femoral and tibial components.

Limitations

First, this cadaveric study used only eight specimens collected from five donors (female (2 unilateral, right and left), male (3 bilateral) ~~and~~. ~~although~~ Although the study's power was adequate [60], ~~the~~ sample size ~~was~~ is still small and the inclusion of more specimens may provide a better understanding of native knee laxities. Second, the age of the specimens used in this study might not represent a typical age range for TKA. Moreover, the mechanical properties of the soft tissue alter with advancing age (i.e., lower ultimate load with respect to young individuals) [61], this might have had an impact on the ligament stability. Nevertheless, as each specimen served as its own control—collateral ligament strains of the knee were compared before and after TKA without any mechanical alterations—this is not expected to have had an impact on the conclusions of this study. Third, with the use of cadavers, artificial load was applied, and this may not represent physiologic load. ~~Third~~Fourth, although the quadriceps traction is dictated through a linear actuator and the quadriceps clamp is mounted to an actuator with a ball-socket joint which allows multiaxial rotations, it remains unknown to what extent this setup replicates the physiological behavior of patellar motion. Fifth, as this study only focused on comparing the native knee to its post-op condition, a major limitation of this study is the lack of a parallel comparison to other balancing techniques. As such, our study design does not allow to conclude if this technique is superior to any other balancing technique. Nevertheless, to the best of our knowledge, no other technique is currently available in the literature that separately balance the medial and lateral compartments while maintaining the patella in the reduced position. Sixth, we only compared the tibiofemoral kinematics and collateral ligament behavior following single radius TKA (Stryker Triathlon) to its native condition. Although we assume that the PIPB technique could work with other single-radius TKA designs, we have no data to support this. In addition, many contemporary designs display posterior femoral condyles with a single curvature radius, which aims at ensuring isometry of the collateral ligament throughout the flexion range of motion. Last, we cannot currently ~~link~~ corroborate any of these experimental findings with clinical outcomes scores.

Conclusion

Many studies suggest that patellar eversion during TKA has a strong influence on intraoperative femorotibial joint gap measurement. With this study we demonstrated to what extent the presented Patella-in-Place balancing technique, succeeds in reconstructing native kinematics and ligament elongations with a standard implant. As such, post-operative laxity was found to be smaller in both valgus and varus than in the native situation. Our technique has successfully achieved the surgical target in terms of a full range of flexion motion, no slackness, symmetrical medial/lateral balance, good patellar tracking over the complete range of motion—especially for the patellar translation— and comparable femoral rollback on the tibia, despite slightly reduced rollback medially and increased rollback laterally. Although balancing with this novel Patella-in-Place balancing technique shows promising biomechanical results *in vitro*, further *in vivo* studies are required to assess the success rate using same type of implants. Moreover, we are planning to investigate the biomechanical impact of the PIPB technique in terms of kinematics and collateral ligament strain for different TKA designs and ~~using the PIPB technique~~balancing techniques.

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Fig. 1 Experimental setup and surgical procedure: (a) dynamic knee simulator, (b) transcondylar pin drill guide upper part fixed to the IM rod ,(c) transcondylar pin drill guide lower part ,(d) attachment of the special keeper on the threaded pin, (e) intraoperative balancing steps.

Fig. 2 Adduction and abduction in the native knee and TKA conditions during application of a 10 Nm varus or valgus moment at 0°, 30°, 60° and 90° of flexion. The data is represented as mean (across the specimens) and the relative change in varus or valgus that occurs throughout the application of load with respect to the neutral, unloaded position at each flexion angle, defined as 0°.

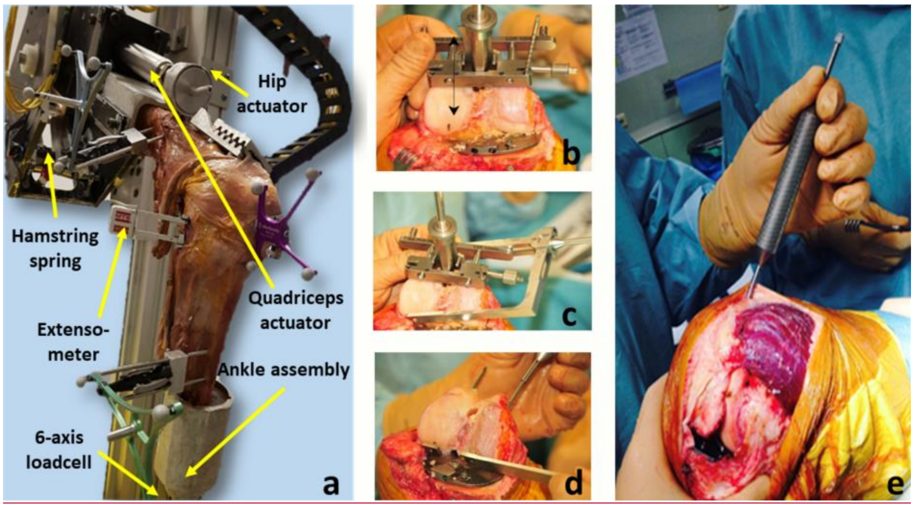
Fig. 3 Medial collateral ligament (MCL) and Lateral collateral ligament (LCL) strains (%) in the native knee and TKA conditions during application of a 10 Nm varus or valgus moment at 0°, 30°, 60° and 90° of flexion. The data is represented as mean (across the specimens) percentual change in length that occurs throughout the application of load in either the MCL or LCL strain with respect to the neutral, unloaded position at each flexion angle, defined as 0%.

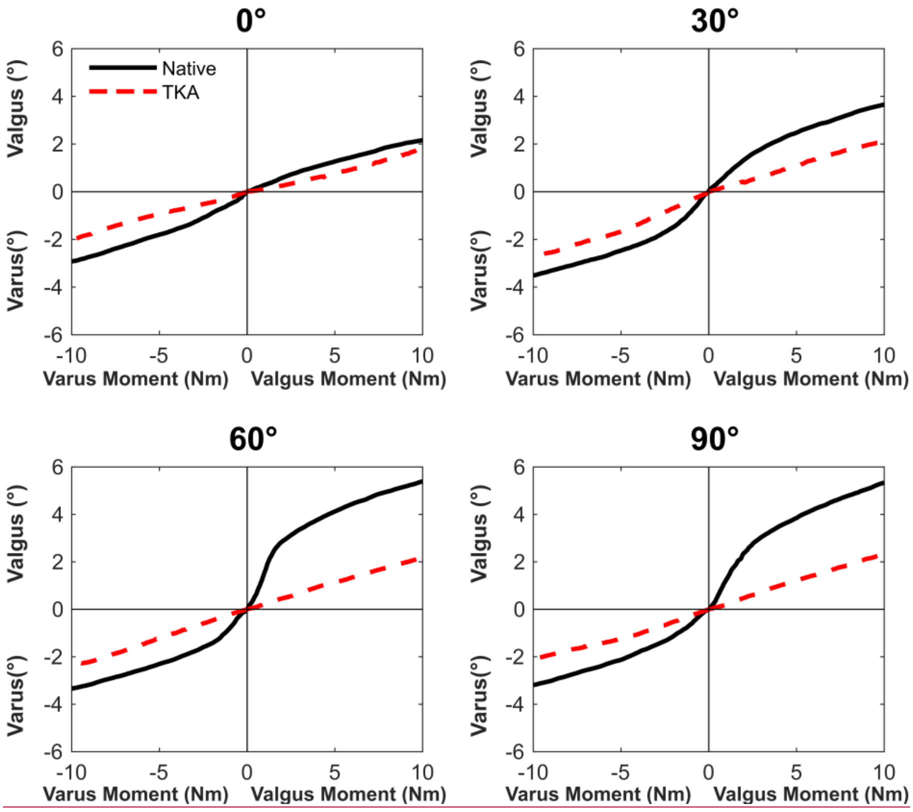
Fig. 4 Kinematics of the knee in the native condition (black) and TKA (red) conditions during passive flexion (left) and squatting (right): (a,e) tibial valgus orientation (b,f) tibial internal rotation (c,g) medial collateral ligament strain and (d,h) lateral collateral ligament strain. Data is represented as mean (solid) ± SD (shaded) across the specimens. MCL=Medial collateral ligament and LCL=Lateral collateral ligament.

Fig. 5 Mean femoral rollback patterns across the specimens observed during passive flexion and squatting. Solid dots represent the respective centers of the medial and lateral femoral condyles. Data were normalized to the size of the specimen’s tibial plateau. 0 represents posterior/medial and 1 represents anterior/lateral.

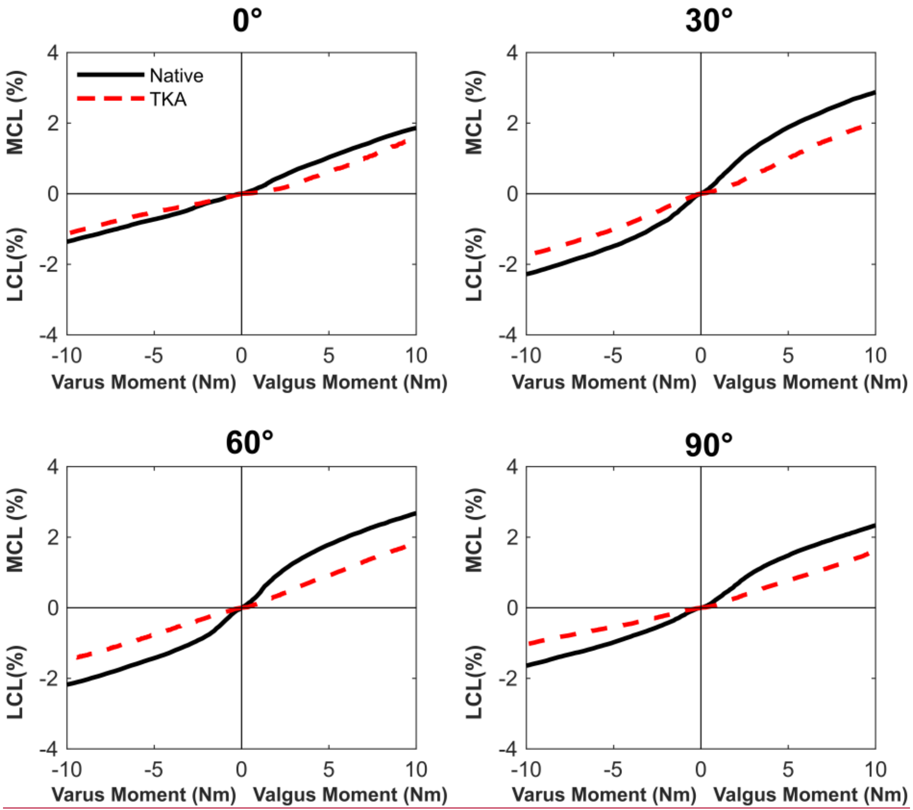
Fig. 6 Patellofemoral kinematics in the native (black) and TKA (red) conditions during squatting: (a) flexion of the patella, (b) abduction (medial (+)/lateral (-)), (c) tilting (medial(+) and lateral (-)), (d) anterior (+)/posterior (-

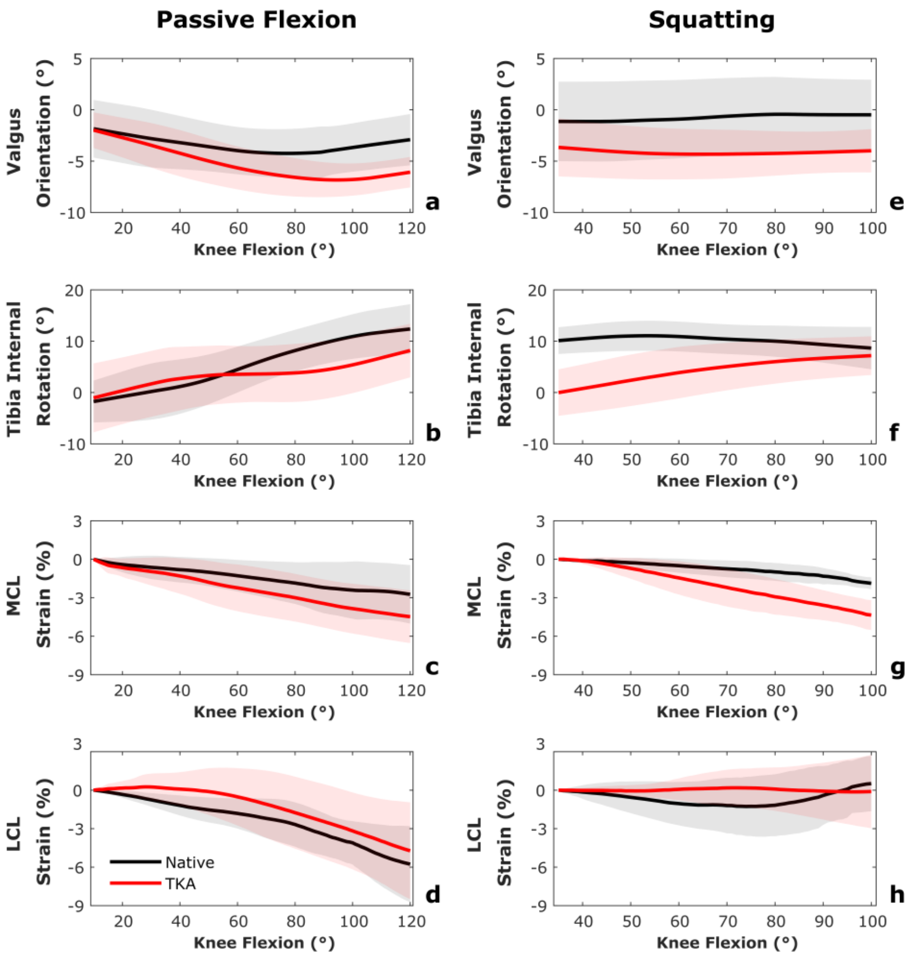
) translation, (e) medial (+)/lateral (-) translation and (f) inferior (-)/superior (+) translation. Data is represented as mean (solid) ± SD (shaded) across the specimens. The black arrows on 3-D model indicate the motion direction while blue solid lines demonstrate axis of motion. AP=Antero-posterior, ML=medio-lateral and IS=infero-superior.

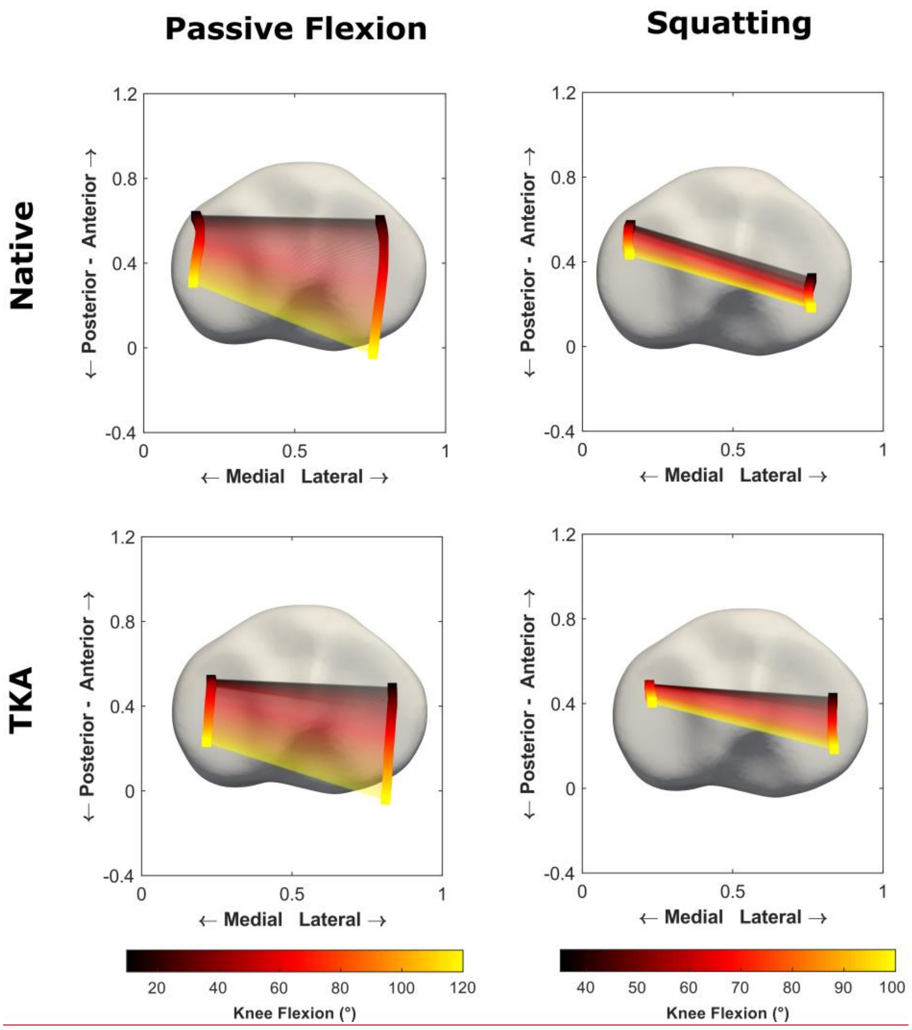


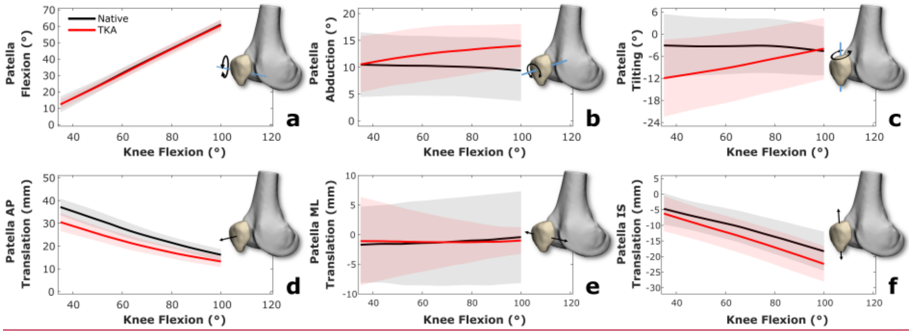

0°
30°
60°
90°
Native
TKA
Valgus (°)
Varus(°)
6
4
2
0
-2
-4
-6
-10
-5
0
5
10
Varus Moment (Nm)
Valgus Moment (Nm)

596


0°
30°
60°
90°
Native
TKA
MCL (%)
LCL(%)
4
2
0
-2
-4
-10
-5
0
5
10
Varus Moment (Nm)
Valgus Moment (Nm)


Passive Flexion
Squatting
Valgus Orientation (°)
Tibia Internal Rotation (°)
MCL Strain (%)
LCL Strain (%)
Knee Flexion (°)
a
b
c
d
e
f
g
h
Native
TKA
5
0
-5
-10
20
10
3
-3
-6
-9
20
40
60
80
100
120
40
50
60
70
80
90
100


Passive Flexion
Squatting
Native
TKA
← Posterior - Anterior →
← Medial Lateral →
1.2
0.8
0.4
0
-0.4
0
0.5
1
20
40
60
80
100
120
Knee Flexion (°)
40
50
60
70
80
90
100
Knee Flexion (°)


Native
TKA
Patella Flexion (°)
70
60
50
40
30
20
10
0
40
60
80
100
120
Knee Flexion (°)
a
Patella Abduction (°)
20
15
10
5
0
b
Patella Tilting (°)
6
0
-6
-12
-18
-24
c
Patella AP Translation (mm)
50
40
30
20
10
0
d
Patella ML Translation (mm)
10
5
0
-5
-10
e
Patella IS Translation (mm)
5
0
-5
-10
-15
-20
-25
-30
f