



# The evolution of patellofemoral prosthetic design in total knee arthroplasty: how far have we come?

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- Total knee arthroplasty (TKA) has evolved into a successful, cost-effective treatment for end-stage knee arthrosis.
- The patellofemoral articulation in TKA has largely been ignored during its development despite being an important determinant of outcome.
- New technologies still need further development to incorporate the patella in TKA surgical planning and operative technique.
- Alternative approaches to alignment in TKA will have a secondary impact on patellofemoral mechanics and possibly future implant designs.
- Technologies that assist with precise implant positioning may alter our understanding and overall practice of TKA.

**Keywords:** evolution; patellofemoral prosthesis design; total knee arthroplasty

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## Introduction

Total knee arthroplasty (TKA) is generally described as a successful, cost-effective treatment for patients with end-stage arthritis of the knee,<sup>1-3</sup> and it certainly is for 80% of patients.<sup>4,5</sup> Since the innovations of the early 1970s, considerable advances have been made in terms of component design, peri-operative care, alignment strategies, surgical approaches, and, more recently, the use of advanced technologies such as computer navigation and robotic-assisted surgery to improve patient outcomes.<sup>6-11</sup> The patellofemoral part of TKA, however, has a history of neglect despite the patellofemoral articulation being an important aspect of TKA that has a profound impact on outcome and may be a composite indicator for the overall success of the procedure.<sup>12</sup> During this review, we will outline the evolution of design of the patellofemoral part of TKA and highlight the areas in much need of further research.

## Early innovations

Early attempts at anatomical knee arthroplasty focused on the tibiofemoral articulation and were used to treat severe axial deformities as a result of rheumatoid arthritis and tuberculosis.<sup>13</sup> The patellofemoral joint (PFJ), however, was largely ignored. Innovations such as the Freeman-Swanson Total Condylar Prosthesis (1970) and the Kodama-Yamamoto prosthesis (1970), paved the way for future designs, yet the original versions made no allowance for the patella.<sup>14,15</sup> Patellectomy was frequently performed either at the primary procedure, or subsequently for patellofemoral pain and instability.<sup>13,16</sup>

Parallel to the development of the total knee replacement was the evolution of isolated PFJ arthroplasty, which had humble beginnings with the use of a Vitallium prosthesis secured with a single transfixing screw to resurface the patella alone, as described by McKeever in 1955,<sup>17</sup> reportedly showing good functional results, and offering an alternative to patellectomy in isolated patellofemoral arthrosis.<sup>18,19</sup>

Early TKA pioneers soon revisited their designs when extensor mechanism dysfunction and anterior knee pain became evident. For example, in 1973 the total condylar prosthesis was redesigned to include a proximal flange that could accommodate a resurfaced patella;<sup>20</sup> Groeneweld reported on the use of an all polyethylene (PE) patellar resurfacing with the Münster-TKA;<sup>21</sup> and Hanslik reported on the use of a modification of the McKeever patellar resurfacing prosthesis with the Young hinged knee in 1973.<sup>22</sup> From 1975, authors such as Aglietti, Insall and Mathews were investigating the biomechanics of the patellofemoral joint and highlighted the importance of design considerations that could accommodate the high-contact stress witnessed in experimental models of patellar prostheses.<sup>23,24</sup>

Patellar resurfacing became an integral part of TKA, and authors were reporting promising results, albeit with potential risks such as patellar fracture, implant loosening, component wear and instability. Many of these issues are unresolved, and the orthopaedic community remains

divided in terms of whether, when and how to resurface the patella during TKA.<sup>16</sup> With accumulating clinical experience and improved understanding of the biomechanical nature of the PFJ, five key areas have emerged as having a profound impact on the patellofemoral articulation in TKA, including (i) the shape of the femoral and patellar components, (ii) the position and alignment of the components, (iii) bone preparation, (iv) the materials used, and (v) the impact of tibiofemoral stability on the patellofemoral articulation.

### Shape of the components

Advances in imaging modalities, the development of validated finite element analyses, and well-designed cadaver studies have improved our understanding of the kinematics of the patellofemoral articulation. A deepened trochlear groove with a lateral wall build-up appears to improve patellar tracking, tilt and contact profiles.<sup>25,26</sup> Valgus trochlear alignment of 7° reduces lateral shear forces at low flexion angles in comparison with neutral trochlear alignment, but this difference lessens at flexion angles close to 90° due to the concurrent distal translation of the patella relative to the trochlea in deep flexion.<sup>27</sup>

The kinematics in unresurfaced versus resurfaced patellae are affected by trochlear shape. A trochlea with a V-shaped axial profile has been shown to generate less contact stress in unresurfaced patellae, whereas with resurfaced patellae, a curved femoral component that accommodates a dome-shaped patellar prosthesis demonstrates favourable contact forces,<sup>28</sup> highlighting the importance of appropriate implant choice to match the surgical strategy.

Buechel, Pappas and Makris studied five patellar resurfacing designs in TKA in 1991, and highlighted that the lack of stringent regulation for design alteration in TKA prostheses permitted manufacturers to release inadequately tested prostheses that led to early failures, again suggesting the relative lack of attention to the patellofemoral articulation in design.<sup>29</sup>

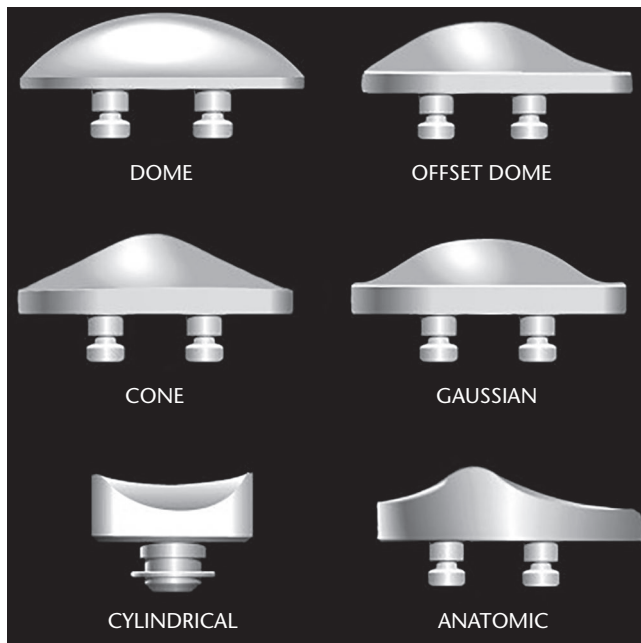
Whiteside's group studied the contact stress in unresurfaced patellae using five different TKA designs in 2000 and demonstrated that the trochlear design plays an important role in the level of stress in the PFJ. They also correlated high-contact stresses with poorly conforming designs that had high rates of anterior knee pain, such as the Insall-Burnstein and Miller-Galante designs.<sup>30</sup>

In 2014, Dejour's group highlighted the plethora of trochlear designs in available TKA implants when they studied the profiles of 14 commonly used implants, demonstrating considerable variation in proximal extension, width, sulcus angle and depth of the trochlea, and the resemblance that many designs have to dysplastic trochlea.<sup>31</sup> For example, 13/14 designs had a sulcus angle > 143°

in the Brattström view (30° flexion), and 8/14 had a lateral facet < 5 mm high at 30–45°. Although manufacturers have made improvements in more recent generations of TKA implants, the trochlear part in newer designs remains 3–6° shallower than normal native knee anatomy.<sup>11</sup> They also demonstrated similar concerns regarding patellofemoral arthroplasty designs.<sup>32</sup> Recently, Werth et al demonstrated the greater tendency for older implant designs with lateral trochlear heights > 5 mm to require secondary patellar resurfacing due to patellofemoral pain following TKA and highlighted that the optimal design characteristics of the patellofemoral joint should take into consideration an anatomically shaped, asymmetric, non-dysplastic trochlear groove with appropriate medial and lateral facet height.<sup>33</sup>

Bonnin et al analysed the shape of 114 arthritic knees using pre-operative CT scans prior to primary TKA and, after comparing this to the corresponding morphometry of 12 TKA models, demonstrated that most femoral components appeared to be excessively rectangular at the level of the distal femoral resection.<sup>34</sup> Intra-operative compensations for this may alter the chosen size or rotation of the component, which may in turn impact on the patellofemoral mechanics.

The patellar component design can be categorized broadly as anatomical, dome-shaped, or cylindrical, with some variations within these categories (Fig. 1 and Fig. 2). The first reported patellar resurfacing by Groeneveld et al made use of an anatomical design with the Münster condylar-type TKA.<sup>21</sup> The anatomical prostheses, which are highly conforming, have shown the most impressive *in vitro* contact stress properties but are unforgiving – malposition of the femoral or patellar components can result in instability, increased wear, increased shear stress at the prosthesis–bone interface, and anterior knee pain. Mobile bearing anatomical components (e.g. Buechel-Pappas, Endotec, Orlando, USA) aim to accommodate this, and showed promising results, but have faced complications associated with metal backing and inter-prosthesis dislocation.<sup>29,35,36</sup> Dome-shaped patellar components (e.g. AGC, Biomet, Warsaw, USA) can be forgiving in the appropriately conforming femoral component.<sup>13</sup> However, they have a propensity for increased contact stress and subsequent wear in higher degrees of flexion within a deepening femoral sulcus,<sup>13</sup> and are at a disadvantage for wear, since bearings perform best when softer materials are concave rather than convex.<sup>37</sup> The modified dome or Gaussian shape with a convex centre and concave rim (resembling a 'sombbrero' in cross-section) reduces contact stress in deep flexion,<sup>38</sup> and the offset dome (e.g. Triathlon, Stryker, Kalamazoo, USA) allows medialization of the patellar component to improve tracking. The dome, or a variation thereof, remains the most frequently utilized design for the patellar component. Cylindrical designs have also shown reduced contact stress but faced concerns about fracture from a



**Fig. 1** Predominant design configurations for patellar components, namely dome-shaped, anatomical and cylindrical, or a variation of these.

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large central peg, over constraint, and the use of an inlay technique.<sup>13</sup>

## Preparation of the patella

The McKeever prosthesis, and subsequently Hanslik's PE modification, were applied in an 'overlay' fashion after reshaping the patella sufficiently to fit the retropatellar surface within the prosthesis, which was then transfixed with a single screw. Since these early attempts, two strategies for patellar resurfacing have emerged, namely, the onlay technique where the patella is placed onto the cut retropatellar surface, and the inlay technique where the patella is placed within a reamed cavity thereby preserving the surrounding bone. In order to achieve favourable patellar tracking and reduce the risk of patellar fracture, the objective for the onlay technique is to obtain a uniformly thick patellar remnant of no less than 12 mm while restoring the native height of the patella with adequate medialization of the highest point of the prosthesis. Comparative studies are small in number and cohort sizes, with no clear benefit being attributed to either technique,<sup>39,40</sup> yet the onlay technique is the most frequently utilized and arguably more versatile than the inlay technique.

Inaccurate resection with any technique is not uncommon, even amongst experienced surgeons, and leaving

the patella too thick, too thin, or asymmetrical in the coronal or sagittal plane has been linked to patellar maltracking, abnormal kinematics, increased risk of fracture, loosening, patellofemoral impingement and anterior knee pain.<sup>41–44</sup> Patellar cutting guides may assist in providing a uniform resection, but in reality, currently available systems are highly dependent on correct application, and do not appear to be more accurate than freehand technique in experienced hands.<sup>45</sup> Furthermore, the depth of the patellar resection cannot be considered in isolation, and an appreciation of the corresponding femoral resection is required.<sup>46</sup>

Technological aids such as computer-assisted surgery and robotics have not formally incorporated the preparation of the patella into the surgical technique. However, Belvedere et al were able to use a secondary navigation system to monitor patellar kinematics intra-operatively to evaluate the quality of the patellar resection and component position,<sup>47</sup> and Fu et al have demonstrated the feasibility and accuracy with the use of a computer-assisted patellar resection in experimental models.<sup>48</sup>

## Component position

Patellofemoral kinematics are inextricably linked to tibiofemoral kinematics – one cannot be altered without a significant impact on the other.<sup>49–51</sup> Femoral and tibial component rotation, translation and flexion, patellar translation and posterior condylar offset are key considerations. Despite advances in design, patellar kinematics in TKA differ considerably from those seen in the native knee.<sup>50,51</sup>

In the early 1990s, Whiteside's group compared cadaver patellar tracking and knee stability to that of TKA using the Ortholoc II prosthesis.<sup>51</sup> External rotation of 5° provided better stability and patellar tracking than neutral or internal rotation. It was postulated that the external rotation compensates for the orthogonal proximal tibia cut, which is approximately 3° from the native proximal tibial varus joint line.<sup>51</sup> However, external rotation may create excessive asymmetry in the posterior condyles, with detrimental effects on the tibiofemoral stability and lateral overhang.<sup>52</sup> A more recent finite element analysis has demonstrated that femoral component internal rotation can increase the patellofemoral contact forces two-fold in comparison with femoral component external rotation, especially in conditions of deep knee flexion.<sup>53</sup>

Anglin et al studied 11 different positions of femoral, tibial and patellar components and described the impact that these had on patellar tracking, using the NexGen TKA in cadaver models. They confirmed that femoral component external rotation can improve patellar tracking, but is limited by the impact on tibiofemoral mechanics; tibial component rotation has a small impact on patellar tracking; patellar resection angle influences tilt and shift, and requires more attention than previously thought; and patellar medialization improves patellar



**Fig. 2** Examples of femoral components with their respective patellar implants. Top row, from left to right: AGC® (dome-shaped patella), Biomet, Warsaw, USA; Buechel-Pappas (uncemented anatomical rotating platform patella), Endotec, Orlando, USA; LCS® (anatomical fixed bearing patella), DePuy, Warsaw, USA; Medial rotating knee® (cylindrical patella), Finsbury, England. Bottom row, from left to right: Journey® (offset dome patella), Smith and Nephew, Andover, USA; PFC-Sigma® (modified dome patella), DePuy; Triathlon® (offset dome patella), Stryker, Kalamazoo, USA; Bio-Pro® Townley Total Knee Original (uncemented metal-backed dome patella), Biopro®, Port Huron, USA. Reproduced with permission from Schindler OS. The controversy of patellar resurfacing in total knee arthroplasty: *Ibisne in medio tutissimus?* *Knee Surg Sports Traumatol Arthrosc* 2012;20:1227–1244.

shift, but excessive medialization (beyond 2.5 mm) can increase patellar tilt.<sup>42</sup> They noted the significant contribution that soft tissues play in patellar kinematics, especially at 90° of flexion. Patellar medialization is also supported in other studies.<sup>25,27</sup>

Increasing posterior condylar offset by more than 2 mm and decreasing the tibial slope both increase the patellar contact forces and should be avoided.<sup>54</sup> Maximal coverage of the patella by the patellar component has been associated with improved patellofemoral load distribution.<sup>55</sup> Increasing PE thickness and the patellofemoral offset have been shown to reduce knee range of motion exponentially in cadaver models,<sup>56,57</sup> and increase the lateral patellar tilt.<sup>58</sup>

The overall alignment strategy may also have a significant impact on the patellofemoral articulation, and optimal limb alignment has long been regarded as an important factor determining outcome and longevity in TKA.<sup>59</sup> However, what constitutes optimal alignment is still a matter of debate.<sup>60,61</sup> Classically, two alignment strategies were described: (1) anatomical alignment, which aims to achieve a neutral hip–knee–ankle angle with the anatomical joint line orientation of 2–3° from the horizontal to bring the joint line parallel to the floor during single leg stance;<sup>62</sup> and (2) mechanical alignment, which aims to restore a neutral mechanical axis with orthogonal femoral and tibial resections and subsequent soft tissue balancing, in order to distribute load evenly

through the implant bone interface. The latter has become the gold standard.<sup>63</sup> More recently, an alternative alignment strategy has been studied, namely kinematic or functional alignment, which is based on a three-dimensional appreciation of the single axis of rotation of the knee.<sup>8–10</sup> In this approach, the objective is to position the implants so as to restore the pre-arthritic knee anatomy, permitting motion more akin to native knee motion. In the coronal plane, the native distal femoral valgus and proximal tibia varus are respected to create a joint line orientation angle approximately 3° from the horizontal.<sup>9,10</sup> In the sagittal plane, the native tibial slope is maintained, since cruciate-retaining implants are usually utilized, and in the axial plane the distal femoral rotation remains neutral, rather than externally rotated as desired with mechanical alignment.<sup>10</sup> While some institutions have reported promising short and mid-term results, clinical and biomechanical studies remain divided regarding which is the optimal strategy to employ.<sup>60,64–71</sup> Furthermore, alternative alignment strategies will have a secondary impact on the patellofemoral mechanics and possibly the evolution of implant designs, and will require further evaluation.

## Materials

Modern TKA with patellar resurfacing most frequently involves a cobalt-chromium femoral component with a PE patellar component.<sup>72</sup> However, numerous materials have



been tried with varying success. McKeever's patellar prosthesis, designed to articulate with the native trochlea, was fashioned from Vitallium, which is an inert alloy composed predominantly of cobalt and chromium with good resistance to corrosion and well documented use in orthopaedics from the early 1940s.<sup>73</sup> Hanslik utilized a high-density PE variant of McKeever's design to resurface the patella with the Young hinged knee from 1969 in 46 patients and described good function and pain relief in the majority of cases.<sup>22</sup> Gunston and MacKenzie designed a stainless steel patellar button that articulated with a PE track in the trochlea with the polycentric knee system and described promising results in 1976, but cautioned about potential complications of additional prosthetic components.<sup>74</sup> Groeneveld described the use of an anatomical three-peg PE patellar prosthesis with the Münster TKA in 1973, and soon thereafter other innovators described the use of PE patellar components with condylar-type TKA prostheses.<sup>16,21</sup> Metal-backed patellar designs were introduced in the 1980s since they were shown to improve load transfer and allow for biological fixation in tibial and acetabular components. But decreasing the relative thickness of the PE to accommodate for the metal back, increasing the patellofemoral offset and imperfections in patellar alignment, contributed to complications such as PE fatigue failure, patellar fracture and implant dissociation.<sup>36,75</sup> Carbon-fibre-reinforced PE showed inferior wear and fatigue fracture characteristics.<sup>76</sup>

Improvements in the manufacturing process for PE, including heat annealing, appropriate doses of gamma radiation, vitamin-E enrichment, and avoiding a prolonged shelf life have improved strength and wear properties.<sup>13,77,78</sup> However, the biomechanical stresses in TKA cannot be compared with those seen in total hip arthroplasty, where the focus of research has been for these new developments in PE processing, and the long-term mechanical properties remain to be delineated in TKA.<sup>79</sup>

Oxinium has been used successfully in TKA,<sup>80,81</sup> but has not demonstrated superiority to cobalt-chromium implants.<sup>82,83</sup> Ceramics have faced challenges with regard to fixation at the implant bone interface, but have also shown good survivorship at 10 and 15 years in TKA.<sup>84–86</sup> Polyetheretherketone (PEEK) is currently being investigated as an alternative material in TKA and has shown promising results in vitro.<sup>87</sup>

### Effect of tibiofemoral stability

There is a paucity of literature demonstrating the impact that tibiofemoral stability has on the PFJ, and the impact this has on TKA. Femoral rollback, a characteristic of native knee kinematics, is achieved by an intact posterior cruciate ligament (PCL) or cam-and-post mechanism and permits greater degrees of knee flexion. It effectively lengthens the

patellar moment arm, which increases the efficacy of the extensor mechanism but also increases the contact forces in the PFJ, which can be detrimental to the joint.<sup>88</sup> Increasing the patellofemoral offset will exacerbate this. In cadaver models, removal of the anterior cruciate ligament (ACL) appears to create substantial lateral patellar tilt and lateral patellar translation, which is restored with ACL reconstruction.<sup>89</sup> Similarly, PCL deficiency appears to alter patellar flexion, lateral translation, rotation and tilt, which are restored, in part, by PCL reconstruction.<sup>88,90</sup>

### Patellar resurfacing or not

After initially ignoring the patellofemoral joint during TKA, then making patellar resurfacing a routine part of the procedure within the same decade,<sup>91</sup> when the potential complications of patellar resurfacing became apparent, three main approaches emerged – those who never resurface, those who routinely resurface, and those who selectively resurface the patella. Even today, there is much controversy in this debate,<sup>92</sup> with clinical, economical and medicolegal considerations influencing the chosen approach.

Proponents of resurfacing suggest it reduces post-operative anterior knee pain, avoids revision and secondary resurfacing, avoids cartilage–metal articulation which causes cartilage wear, and improves patient outcomes.<sup>13,93–95</sup> Opponents of resurfacing argue for maintaining patellar bone stock, reducing operative time, maintaining physiological patellofemoral kinematics, and avoiding complications associated with resurfacing.<sup>96–98</sup> Complications such as maltracking and anterior knee pain are usually a result of errors in technique, or design, or both, and simply resurfacing the patella secondarily does not always resolve the symptomatic unresurfaced patella.<sup>12</sup>

Applying strict criteria (patients < 65 years old, without advanced patella cartilage loss or inflammatory arthropathy, central patellar tracking and the appropriately designed prosthesis) to selective patellar resurfacing has produced high survival rates at 10 years.<sup>99</sup> However, it has been highlighted that manufacturers provide femoral components that have varying degrees of 'patella-friendly' trochlear designs,<sup>99</sup> and care should be taken when selecting the appropriate implant.

Zangger and Detsky determined the mean probability of complications associated with patellar resurfacing versus non-resurfacing, and used a Bayesian model to demonstrate that even with the help of a computer-based decision model and available data, there is no difference in overall risk between resurfacing or not resurfacing, and either approach can have arithmetically similar advantages and disadvantages.<sup>100</sup> This may indicate that we have a long way to go before we fully understand the patellofemoral articulation.

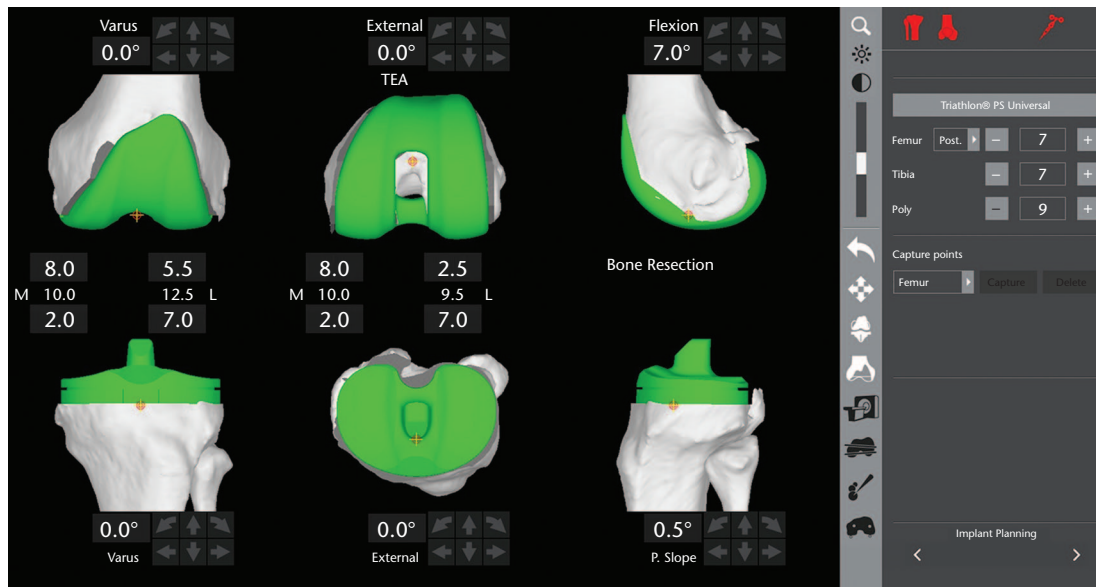


Fig. 3 Screen capture of pre-operative plan for a robotic-assisted total knee arthroplasty.

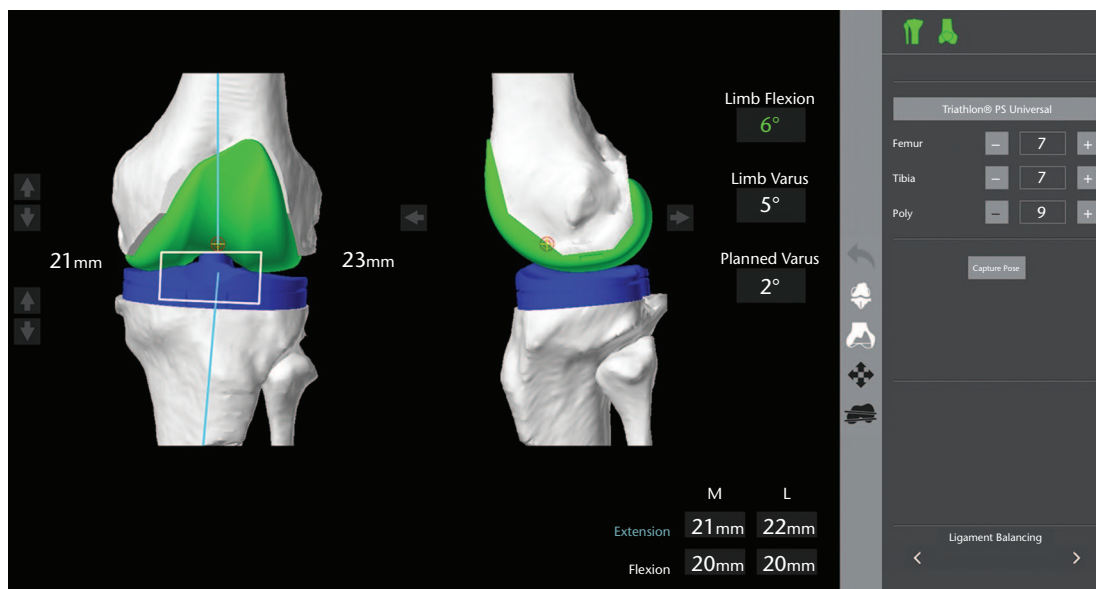


Fig. 4 Intra-operative screen capture of a robotic-assisted total knee arthroplasty during assessment of soft tissue balance prior to performing distal femoral and proximal tibial resections.

Meta-analyses have failed to demonstrate a clear benefit from patellar resurfacing versus non-resurfacing in TKA in terms of pain, functional outcome scores, patient satisfaction, and complication rates.<sup>101</sup> The risk of re-operation has repeatedly been shown to be higher in patients undergoing patellar resurfacing,<sup>102–105</sup> yet when only evaluating high-quality randomized controlled trials, He et al demonstrated equivalent results.<sup>104</sup> Interestingly, no high-quality meta-analyses have reported superior outcomes for non-patellar resurfacing.<sup>101</sup> Concerns with

selection bias, relatively small sample sizes, heterogeneity in terms of outcome metrics and numerous confounding variables that influence the outcome after TKA (as discussed above), encumber our ability to evaluate the question of whether or not to resurface the patella.<sup>101</sup> If we are to obtain the answer to this question, it will require well-designed studies with adequate control of confounding variables that are able to identify potential individual characteristics predictive of good outcomes rather than pooling heterogeneous data.

## Generation 'R'

Fast-track to 2019, and we have at our disposal advanced technologies such as computer navigation and robotic-assisted surgery, which allow us to plan and achieve the desired component position, limb alignment and soft tissue balance with increasing accuracy for the tibial and femoral components.<sup>106,107</sup> Yet we still ignore the PFJ to a large extent with key determinants of patellar tracking not included in the operative planning or execution – the patella is not visible on the pre-operative plan (Fig. 3), which precludes an evaluation of the depth of resection and component position, and the final intra-operative preparation to accommodate femoral and tibial component translation is performed manually, as is the rotation of the tibial component and the patellar resection. Tibiofemoral range of motion and coronal balance are evaluated with the navigation system intra-operatively, but patellar tracking and soft tissue balance are not (Fig. 4).

Technologies that allow us to place implants in the exact position in which we want them may influence our surgical goals in TKA, and we will need to utilize them efficiently in order to understand the optimal solution for our individual patients.<sup>108,109</sup> They may also assist in controlling some of the confounding variables that make outcomes in patellar resurfacing *versus* non-resurfacing difficult to compare.

## Summary and recommendations

We have seen considerable design and technological advancements in TKA since the ground-breaking work of the early 1970s. The patellofemoral articulation, however, has a history of being ignored. Future research efforts and technological advances will need to incorporate the patellofemoral articulation in the design, operative planning and surgical technique of TKA in order to improve our surgical accuracy, collection of data, and our understanding of this aspect of TKA, which may be a composite indicator of the overall success of the procedure.

The increasing push towards alternative alignment strategies will also cause secondary changes in patellofemoral mechanics, and possibly in the designs of knee arthroplasty. Moreover, the available technologies that now allow us to place implants exactly where we want them, may also improve exactly what we do.

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### CONFLICT OF INTEREST STATEMENT

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