Review article

How does total knee replacement technique influence polyethylene wear?

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A B S T R A C T

In knee prostheses, wear is inherent to the tribology of the imperfectly congruent surfaces, one in chromium-cobalt alloy, the other in polyethylene. It is a multifactorial phenomenon, involving the properties of the respective materials and implant design, but also implant function, as determined by the implantation technique. There are still dark corners in the implantation charge book, especially concerning minimal insert thickness, the adjustment of tibiofemoral alignment and ligament balance. A review of the literature revealed consensus regarding minimal insert thickness (8 mm), tibiofemoral alignment (to be kept within 5° on either side of the neutral axis) and ligament balance (identical collateral ligament tension in both extension and flexion spaces). Finer adjustment seems desirable. Tibiofemoral alignment is probably customizable according to individual patient morphology and weight. The rotational alignment of the components should allow harmonious patellar engagement. Classic ligament balance rules underestimate sagittal laxity, which needs checking to prevent paradoxical movement accelerating polymer delamination. Navigation techniques or specific ancillaries can help optimize implant component alignment. Control of sagittal laxity may require specific adaptation, notably in the flexion space. Improved implantation technique could postpone wear onset until beyond the 10th or even 20th postoperative year, barring material failure for other reasons.

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1. Introduction

Long-term survival is less affected by wear and osteolysis in knee than in hip prostheses. Wear is nevertheless a constant issue, due to the non-congruent and sometimes unstable form of the knee joint, and often leads to implant revision; innovations over the years failed to resolve the problem, which is intrinsic to friction couples comprising chromium-cobalt alloy and polyethylene (PE), which are difficult to avoid for the knee.

Metallic tibial baseplates, for example, were designed to improve implant modularity, allowing defective PE inserts to be replaced while conserving the metal parts fixed to the bone. However, revision for simple insert replacement is rare, and radiographic surveillance alone cannot provide accurate wear alerts. It is quite often only at the “worn-through” stage that revision is indicated, requiring replacement of the tibial baseplate, damaged by friction against the femoral condyle (Fig. 1). Modularity, moreover, entails a new kind of “back-side” wear in the fixed insert. And finally there is no real proof of any advantage of modularity in terms of implant survival compared to “all-PE” components [1].

Congruence between the femoral component and the mobile insert was another focus of improvement, to reduce wear by separating unidirectional sliding at the metal–PE interface from multidirectional rotation at the insert/baseplate interface. Long-term results, however, showed no particular advantage over fixed inserts [2].

Progress with friction-couple materials has been limited: hard–hard couples have not been developed as they have for the hip, due to the incongruence between the surfaces. The most definitive progress has been in improved sterile vacuum packing of inserts, to reduce in-vivo oxidation after implantation. Polished tibial baseplates in chromium-cobalt seem preferable to titanium, which shows poor tribologic relations with PE. For highly cross-linked PE, follow-up is as yet too short to have conclusive results.

These conflicting clinical findings and disappointing innovations raise two questions:

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What is the real rate and clinical impact of wear in knee prostheses?

The surgeon chooses the implant, and notably the thickness of the insert, which is generally available in a range of 4 or 5 thicknesses from 9 to 16 mm. Tibiofemoral alignment and joint stability can also be adjusted, usually medially or laterally to create two rectangular spaces: in flexion (90°) and in extension (0°), according to implant thickness.

We hypothesized that improving technique in terms of choice of implant size, component alignment and adapted balancing will reduce wear and osteolysis without compromising function. We therefore successively discuss the 3 following technical issues:

1. Can PE insert thickness be optimized?
2. Is tibiofemoral alignment a determining factor?
3. Is the mediolateral balance recommended by Insall enough to limit wear?

2. What is the real rate and clinical impact of wear in knee prostheses?

Wear in the less resistant of the friction-couple materials is an inevitable tribologic consequence of joint replacement functioning. In the case of the knee, the phenomenon at first seemed to be of less clinical importance as the resulting periprosthetic osteolysis rate is lower than in the hip. The low rate of osteolysis and consequent implant loosening was attributed to a specificity of wear mechanisms in the knee: delamination predominates [3], and the imperfectly congruent surfaces release PE particles that are larger than a micron, and thus less biologically reactive (Fig. 2) than those typically produced by abrasion in hip prostheses, in which two perfectly congruent surfaces are in friction [4]. Thus, remarkably good survival was reported for the first generation of total knee replacements, unlike in the hip.

Rodriguez et al. [5] managed to analyze more than 20 years’ follow-up for 45 out of 220 Insall-Burstein total knee replacements with cemented PE tibial component, and reported only 14 failures, including only 6 cases of loosening of at least 1 of the 2 components that could be attributed to wear. Subsequently, such results were rarely reproduced.

Callaghan et al. [6] reported outcome at a minimum 20 years’ follow-up in 16 patients out of an initial series of 75 total knee replacements sparing the posterior cruciate ligament and using a metal tibial baseplate. There were 6 failures, all implicating excessive PE wear. However, the same team [7], reporting a series of active under-55-year-old patients with osteoarthritis, admitted that PE wear is a concern, as 10 out of 39 patients showed osteolysis before 10 years postoperatively, requiring implant revision surgery.

There have also been some occasional reports of medium-term osteolysis rates in more recent implant designs:

- Marion et al. [8] reported 10% medium-term osteolysis using hypercongruent inserts (Fig. 3);
- Tsao et al. reported 7% short-term osteolysis, predominating in young and heavy patients [9];
- O’Rourke et al. [10] reported 16% medium-term osteolysis with a classic Insall-Burstein 2 design.

In 2002, Sharkey et al. [11], analyzing causes of late revision of total knee replacement, primarily incriminated aseptic loosening due to insert wear.

The variability of wear-related failure rates reflects the complexity of this multifactorial phenomenon, which may be latent for several years in case of optimal implant design and implantation technique, but surfaces quickly if one of these parameters is defective. Wear is very difficult to assess on conventional X-ray, and can thus appear suddenly before the 10th year after implantation, in the form of early osteolysis, whenever an implant design or manufacturing parameter proves suboptimal, especially if implantation technique was deficient. Otherwise, wear and its consequences are likely to be in the second decade of use in young active and/or heavy patients; in older and less active patients, implant survival beyond 20 years is not unusual in the absence of major positioning and balancing defects.

3. What leverage does the surgeon have to maximize survival for a given implant design and type of polyethylene?

3.1. Choice of insert thickness

PE insert thickness is limited by the joint space between the distal femoral and tibial bone cuts. Bone resection is usually kept within the thickness of the implant, so as to restore an anatomic joint line; increasing insert thickness thus requires increased resection and bone loss. There is little room for maneuver.

If the insert is too thin, it will be subject to creep, liable to accelerate wear. Pijls et al. [12] advised against PE inserts thinner than 8 mm, based on the calculation that 1 mm reduction in PE thickness...
increased revision rates 3-fold, in a series of 84 knee replacements with modular tibial components. Collier et al. [13] found greater wear in explants with thinner and less congruent inserts. Tsao et al. [9], in a clinical series, reported greater medium-term osteolysis with thinner inserts. Hirakawa et al. [14] likewise found that thinner inserts showed greater superficial delamination and greater backside abrasion.

Ideal PE insert thickness to conserve a physiological joint line is about 11 mm if the cruciate ligaments are sacrificed. Cruciate ligament resection increases flexion space height by 3–4 mm, allowing a thicker insert. If the posterior cruciate ligament is spared, flexion space is narrower. A metal plateau may in that case be detrimental, as the PE thickness is reduced by the thickness of the metal (usually 3 mm).

Generally speaking, “all-poly” tibial components, without metal baseplate, are making a come-back, as clinical results fail to confirm the benefit of using a modular component, in terms of long-term wear [1]. Moreover, in modular tibial components with fixed insert, deterioration of the insert fixation over time leads to backside abrasion [15] proportional to the micromotion between the two components. It is difficult to formulate precise recommendations, but it would seem that a metal baseplate should only be used if it allows a minimum 8 mm PE thickness.

3.2. Adjustment of tibiofemoral alignment

Tibiofemoral alignment is the second parameter liable to affect wear, as it determines load distribution between the two tibial plates. Neutral alignment was traditionally recommended, to maximize survival, with navigation to avoid error exceeding 3°. Theoretic studies confirmed that malalignment increases PE stress [16]. Retrieval studies showed that >5° malalignment increased implant thickness loss by 0.11 mm per year in the concavity of the deformation [17]; Wasielewski et al. [18] found that joint wear and backside creep in the baseplate holes were greater in residual deformation of retrieved inserts.

More recently, several long-term reviews tended to minimize the impact of tibiofemoral alignment on implant survival, which seemed to be at least as good in series aligned with >3° discrepancies from the neutral axis [19]. There are certainly intrinsic factors not taken into account in choosing ideal alignment: patients show individual morphologic differences that can affect loading between plates. Thomine et al. [20] suggested a role for certain morphologic parameters such as extrinsic varus offset of the knee, involving the subject’s weight and pelvic width. Determining ideal “personalized” coronal alignment to distribute load between the two tibial plates thus seems complex and subject to residual laxity in the ligamentous structures of the deformity convexity under loading (Fig. 4), which may be underestimated during surgery, when the knee is not loaded. Hungerford and Krackow [21] recommended an oblique joint line, positioning the tibial component in slight varus compensated by increased valgus in the femoral component to maintain a joint line parallel to the ground in gait. Howell et al. [22] recommended kinematic alignment, respecting the femoral flexion axes. In fact, the impact of these alignment strategies on wear is unknown; in the absence of more precise evidence, it seems reasonable to recommend coronal alignment close to the neutral axis, controlling laxity in the ligamentous structures of the convexity in case of residual deformation, which should not exceed 5°.

3.3. Other

3.3.1. Rotational alignment of the tibial component

Rotational alignment of the tibial component with respect to the femoral component is more difficult to assess, but also seems to underlie wear in case of fixed insert. Tibial component rotation is hard to adjust exactly, as the anatomic landmark (medial edge of the tibial tuberosity) is not precise. The need to optimize tibial cut cover and avoid metal overhang can lead to positioning the baseplate in excessive medial rotation, causing lateral translation of the patella, which may induce lateral subluxation, and hence lateral rotation of the tibia (Fig. 3c). Wasielewski et al. [18] reported a certain number of retrieved implants with greater wear in the posterior part of the medial tibial compartment.

3.3.2. Defective mediolateral alignment

Defective mediolateral alignment between components may cause tibiofemoral subluxation in case of oblique joint line, especially in designs with flat femoral condyles. Wear in this case occurs mainly on the periphery of the medial tibial plateau and medial part of the lateral plateau, as described by Feng et al. [23], who demonstrated a correlation with varus positioning of the tibial component (Fig. 5).
3.3.3. **Defective sagittal alignment**

Finally, defective sagittal alignment, with excessive tibial slope, leads to femoral posterior subluxation during gait (Dejour’s active anterior drawer) in most knee replacements that have lost anterior stabilization due to resection of the anterior cruciate ligament. This leads to posterior delamination, as reported by Wasielewski et al. [18] in retrieved tibial components that had been positioned with excessive slope (Fig. 2).

In all, control of tibiofemoral alignment is not just a matter of HKA angle, but requires controlling the relative positions of each component. Navigation certainly allows control of HKA angle, tibial slope and frontal positioning of the tibial component. Rotational alignment, on the other hand, remains less well-controlled, although navigation can improve reproducibility at least in the femoral component [24]. Adjusting rotation in the tibial component is less precise, and can be affected by the symmetrical or asymmetrical shape of the baseplate. An asymmetric baseplate with smaller anteroposterior dimension in the lateral compartment allows the baseplate to be well-positioned in lateral rotation without risk of posterolateral overhang, which could cause popliteal tendon impingement. Certain “tricks” can improve rotational congruence. Several cycles of flexion/extension of the knee can be performed with trial components in place, letting the insert rotate freely before fixing its final position. When a mobile insert is used, the ideal position for the metal baseplate is that in which insert rotation is unchanged during flexion/extension, fixed by the femoral condyles. This is why it can be useful to use a mobile trial insert, even when the final insert is going to be fixed. It is an argument in favor of mobile inserts, born out by certain retrieval studies which reported less wear than with fixed inserts [25], although this may be counterbalanced by greater abrasion of the backside [26]. This last point makes it clear that mobile inserts should not be used to “correct” rotational positioning errors in the tibial baseplate, and that rotational stress to the insert should be minimized, as should any motion between insert and baseplate.

4. **Ligament balancing**

Residual implant laxity at the end of procedure is incontestably a cause of wear, inducing parasitic anteroposterior translation of the condyles which result in shear stress in the insert surface and delamination of irradiated and/or oxidized PE. Lateral laxity raises the lateral condyle in flexion (“lift-off”) [27], which may be more or less well tolerated depending on the transverse design of the femoral condyles.

The conventional surgical technique consists in balancing tension between the two collateral ligaments by creating two spaces at 90° of flexion and in extension, which are not the positions most frequently adopted in gait. Control of sagittal laxity, on the other hand, tends to be overlooked, and kinematic study of the knees, whether intra- or post-operative, shows many residual paradoxical movements. No implant design avoids this.

4.1. **Posterior-cruciate-substituting inserts with posterior stabilization cam**

In posterior-cruciate-substituting inserts with posterior stabilization cam, anteroposterior stability is lacking in the first degrees of flexion, as the cam is not yet engaged and the knee has no anterior cruciate ligament support. Active anterior drawer during gait is thus unhindered, especially as condyle anterior translation is not greatly limited by the insert’s semi-congruent design. Excessive laxity, compounded by femoral component positioning in flexion and excessive tibial slope, can lead to anterior impingement of the tibial pivot with the metal edge of the femoral component notch, leading to tibial pivot wear and osteolysis [10]. Moreover, repeated
impact of the femoral component against the tibial pivot, whether unintended, as described above, or expected in flexion when the cam is engaged, places stress on the insert fixation onto the baseplate, which may deteriorate and wear the backside of the insert (Figs. 6 and 7).

4.2. Hypercongruent designs

In hypercongruent designs, severe osteolysis has been reported, resulting from a combination of factors: notably, paradoxical anteroposterior laxity in flexion and extension poorly controlled by raising of the anterior and posterior insert edges [28]. Signs of posterior impingement to the posterior edge of the insert in strong flexion have been reported on retrieved implants without tibial slope (Fig. 8), as have traces of posteromedial wear, suggestive of active anterior laxity in extension, in implants with excessive slope [8]. Breakage of the posteromedial part of the baseplate has even been reported, indicating the degree of pressure at that point (Fig. 9). Control of anteroposterior laxity in this type of implant is difficult and variable [28]. Balance has to be improved to optimize on-the-spot slippage of the condyles and enable hypercongruence to play its role. However, increased congruence associated to tightening of the space in flexion increases stress on the insert and its fixation onto the baseplate, with risk of mobilization and backside wear [29].

4.3. Implants sparing the posterior cruciate ligament

With implants sparing the posterior cruciate ligament, 2D fluoroscopy studies of active kinematics found very frequent residual paradoxical movement, indicating imperfect posterior cruciate ligament balance. The resulting slippage can cause wear if congruence is insufficient, as reported in retrieval studies [30]. Theoretic simulation studies found increased wear volume with increasing anteroposterior displacement [31]. In contrast, posterior cruciate ligament sparing may reduce the rate of lateral shift (lift-off) as compared to posterior-stabilized designs, eliminating one possible source of wear, especially in flat condyle designs [27].
4.4. Patellofemoral balance is essential to overall balance

It depends on tibiofemoral balance, as paradoxical condyle movement in flexion increases patellofemoral pressure. It is important to adjust femoral rotation, to optimize patellar engagement. Engagement and balance defects, which often come together, induce patellar incongruence and can lead to severe patellar component wear [32] (Fig. 5b).

5. Discussion

Material-related factors can incontestably cause early wear: notably, PE quality, as physicochemical properties are affected by gamma-ray sterilization, which in turn induces oxidation and premature aging once introduced into an oxygenated atmosphere (on the shelf in vitro, and in vivo). Choice of materials may also be implicated when a PE insert is in friction against a non-polished titanium baseplate. In the vast majority of cases, however, defects in material, which have now been largely corrected, reveal issues of balance or positioning which would otherwise be negligible during the first 10 years. There is thus considerable room for improvement in implant positioning and ligament balance, which is often performed “intuitively”. Progress can be made in identifying reliable landmarks and objectives to optimize reproducible implantation.

To observe such landmarks, which are generally difficult to identify with the naked eye, ancillaries need adapting. For example, how is a paradoxical movement or a posterior drawer to be formally quantified with the implant in place? How is patellar engagement to be assessed apart from major subluxation? How is tibiofemoral alignment to be adjusted to intra-articular pressure? More than the individual positioning of each component, it is probably the functioning of the whole and the positioning of the components with respect to one another that needs assessing: rotational tibiofemoral or patellofemoral congruence. Priorities also need to be determined: should femoral rotation be adapted to tibial positioning, or vice versa? Should navigation set femoral rotation with respect to the trochlear groove or to laxity in flexion?

Defining objectives requires better knowledge of the patient’s individual anatomy. What tibiofemoral alignment is optimally adapted to the patient’s morphology? For example, the patient’s individual varus offset might be calculated.

Possibilities are available: identifying reproducible bone landmarks for adjusting rotation (posterior bicondylar line, Akagi’s line, anterior tibial tuberosity), or patellofemoral alignment (White-side’s line). Using a mobile trial insert in rotation allows tibial rotation to be adjusted to that of the femoral component before definitive fixation. Piriou et al. [33], for example, showed that femoral component positioning by strictly superimposing the prosthetic and native trochlear grooves allows the space in flexion to be balanced. Navigation is not sufficiently used, and could optimize kinematics by measuring the displacement of tibiofemoral contact points during the flexion/extension cycle [28]; it can also precisely measure anteroposterior laxity in reference positions. Controlling sagittal laxity during flexion corresponding to gait flexion is surely the greatest challenge, both functionally, as such laxity correlates with a sensation of instability, and mechanically, as it induces the shear stress implicated in delamination. For example, in case of persistent posterior drawer due to relaxation of the spared posterior cruciate ligament, the flexion space can be tightened by increasing posterior condylar offset. For this, however, the implant design needs to allow tibial and femoral components of different sizes to be used together.

It is clear that these suggestions for improvement involve preoperative planning (calculation of varus offset), navigation (controlling the thickness and orientation of bone cuts, and controlling sagittal laxity), and certain “tricks and tips” for ancillaries. All of this contributes to a more comprehensive charge book for correct knee replacement, which could serve as a check-list at end of surgery:

- minimum 8 mm PE thickness;
- control of tibiofemoral and patellofemoral alignment:
  - tibiofemoral alignment within 5° of the neutral axis,
  - joint line perpendicular to mechanical axis, with patellar height within the physiological range of the Caton-Deschamps index,
  - absence of rotational stress on the tibial component,
  - harmonious patellar engagement (“no-thumb test”) indicating in extreme tibial rotation, reproducing the position of the native trochlea,
  - tibial slope between 0° and 3° in implants sacrificing the posterior cruciate ligament;
- control of sagittal laxity:
  - no Lachman sign in 20° flexion or posterior drawer in 90° flexion,
  - restored or slightly increased posterior condylar offset to avoid both laxity in flexion and posterior impingement in high flexion [34],
  - self-stability of trial insert on its baseplate in high flexion.

6. Conclusion

Minimizing wear is necessary to prolong implant survival in knee replacement. This requires improving the conditions of implant functioning. There is certainly plenty of room for improvement, and it is up to the surgeon, who needs to be equipped with the tools necessary for reproducible implantation without unnecessarily complicating the procedure.

The main prospects seem to lie in improving control of rotational alignment and sagittal laxity throughout the flexion/extension cycle.

Disclosure of interest

Philippe Massin receives royalties from Microport and from Ceramconcept and is a consultant for Evolutis.

References


