Safety of orthopedic implants: implant migration analysis a must

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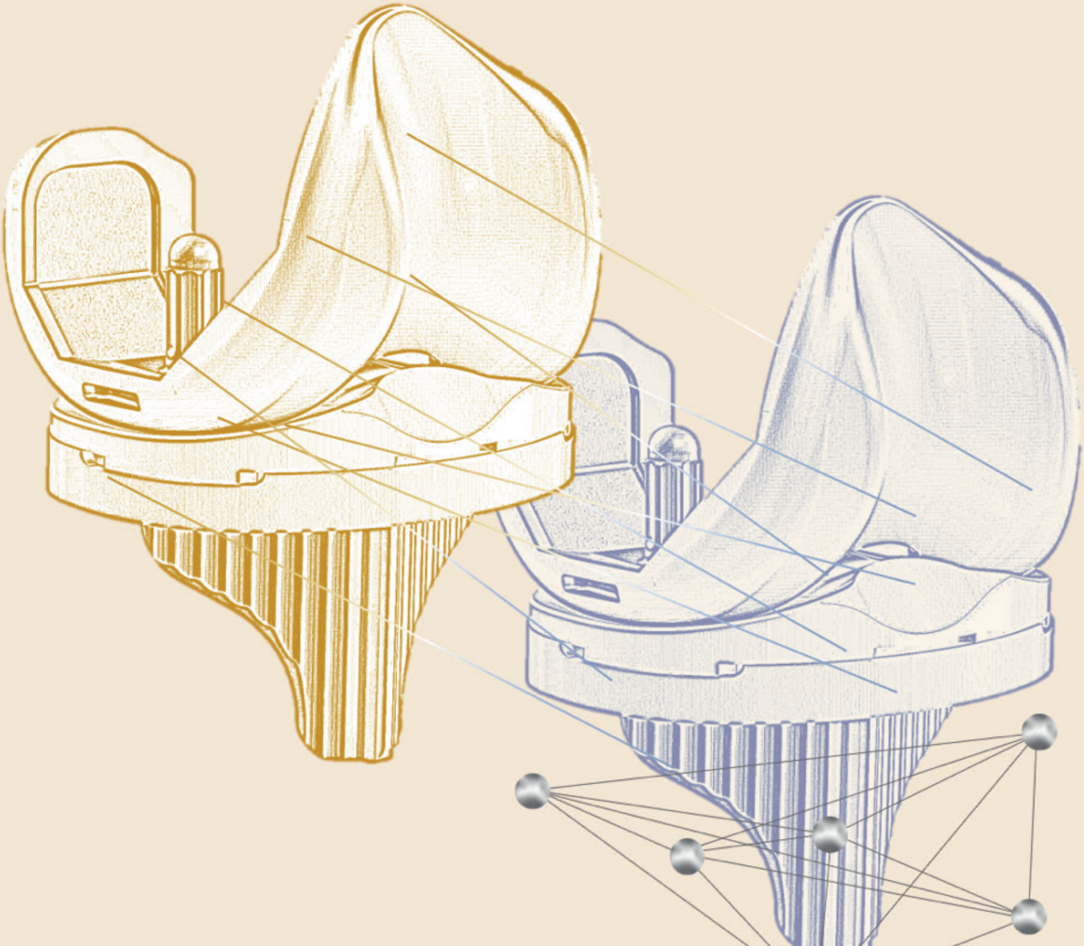


Chapter I

General introduction

Chapter I General introduction and outline

Total knee arthroplasty

Knee osteoarthritis (OA) is a degenerative disease of the knee joint and often leads to knee pain, limitations in daily functioning and a decrease in quality of life.[1-3] Two hundred fifty million people worldwide are suffering from knee OA and the incidence of knee OA has grown dramatically since the 20th century.[4, 5] First line treatment of knee OA include life style advice, physical therapy and oral or intra-articular analgesics.[7] If conservative treatment has insufficient effect on patient complaints, end-stage osteoarthritis can be treated with a total knee arthroplasty (TKA). which has excellent long-term results in the population above 65 years of age. TKA is known to alleviate pain and improve knee function.[8-10] Besides primary OA, other conditions such as inflammatory arthritis, trauma and malignancies can be indications for treatment with TKA.[11, 12]

TKA is one of the most commonly performed orthopaedic surgeries with 25.885 TKAs registered in the Netherlands during the precovid year 2019, which dropped to 21.444 in the covid year 2021.[11, 13] This number is expected to rise in the Netherlands and globally due to an aging population, a longer life expectancy, and an increasing body mass index (BMI), but also due to indications in the younger patients, below the age of 55 years.[14-21] With these rising numbers of TKA performed, the demand and expectations of different patient groups in terms of implant survival and functionality following this procedure is increasing. Therefore, many efforts are put into increasing the longevity in younger age groups but also of functionality following TKA in specific patient groups. Nevertheless, 20% of patients are not satisfied following treatment with TKA, which is in contrast with total hip arthroplasties where less than 5% of patients are not satisfied.[9, 22-31]

Implant design and surgical technique – principles and improvements

The first modern total condylar TKAs date from the early 1970's among which the Freeman-Swanson the Yamamoto and Insall-Burstein total condylar knee protheses. In that time, TKAs consisted of a cemented metal femoral component with a cemented all-polyethylene tibial (APT) component.[32-38] Following this TKA design, Freeman et al. (1973) formulated 14 basic implant design and surgical principles for TKA which have remained highly relevant up until today. Broadly speaking, these entail that loosening and infection should be avoided, wear debris limited as much as possible, a sufficient range of motion should be possible and the implant should be stable through the entire range of motion [Table I.I].[32]

Table I.I Design and surgical principles as proposed by Freeman et al. (1973)[32]

#1	No more bone should be removed as needed for a primary arthrodesis
#2	Loosening should be avoided. This could be minimized by the following principles
	a. The femoral and tibial component should be incompletely constrained to prevent load transfer from the prosthesis to the bone during movement b. Minimalization of friction between both components; Metal-on-polyethylene is therefore preferred over metal-on-metal c. Hyperextension limit should be progressive and not abrupt d. Components should have the largest possible contact area with the bone to spread the load; large bone surfaces on which the prosthesis can sit and the use of cement
#3	The rate of wear debris production should be limited
#4	The produced wear debris should be as harmless as possible
#5	Compact implants with minimal dead spaces should be used to reduce the probability of
#6	The consequence of an infection should be minimized (short stems, avoid intramedullar
#7	A standard procedure protocol should be available
#8	The implant should be able to function from 5° extension to 90° flexion; function above 120
#9	Some freedom in rotation and ad- or abduction should be possible
#10	Soft tissue should resist excessive movements without breaking the bone-prosthesis
#11	It is unwise to depend on the mechanical functioning of the cruciate ligaments for
#12	The prosthesis should permit the removal of intercondylar tissues and should restore
#13	The tibio-femoral replacement should be able to accommodate the patella itself or a
#14	The cost should be minimized by making the smallest practicable number of sizes and versions. This objective is last on the list but should not be forgotten entirely

Due to disappointing survival of APT components, it was thought to improve implant design by adding a modular metal-backed tibial (MBT) component. This modular component would improve results since MBT components showed promising results in biomechanical studies with favourable load transfers to bone.[39-43] Furthermore, they provided intraoperative flexibility as the polyethylene thickness could be adjusted after cementation of the metal-backed tibial baseplate.[44-46] The latter allows in the preoperative planning for different degrees of constraint of the knee implant such as cruciate-retaining (CR) inserts with less constraint, or posterior-stabilising (PS) inserts with more constraint. In some implants these different design options can be exchanged during surgery, if the femoral component is the same, but usually this is not an option since in the PS design a "box" has to be cut at the femoral side to accommodate the PS femoral component. Nevertheless, a non-modular APT component can never be adjusted for constrainment once cemented.[44-46]

An additional benefit of modularity is that the polyethylene insert can be exchanged without need to revise the whole tibial component. Such an insert exchange could be favourable in case of an infection, wear or instability.[44-46] Apart from modularity, another advantage of metal-backed implants is, they can be coated with calcium phosphates to enhance fixation if an uncemented component is used.[45, 46]

A new manufacturing process introduced high cross-linked polyethylene (HXLPE) to modern TKA. This novel HXLPE lowered the wear rate compared to conventional polyethylene (ultra-high molecular weight polyethylene; UHMWPE).[47] However, clinical evidence supporting the use of HXLPE is still limited. Several clinical studies did not show a clinical or radiological benefit of HXPLE and no differences in overall survival between HXLPE and UHMWPE was found in several registries.[48-56] Although, in the Australian Orthopaedic Association National Joint Replacement Registry a higher survival rate of HXLPE TKA was found for specific TKA designs.[57]

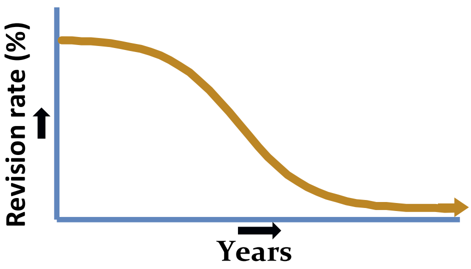
Apart from improvements in material composition, uncemented fixation methods have improved substantially. Ever since the early years of TKA, one of the main reasons for TKA failure was implant loosening.[11, 12, 36, 58] Therefore, fixation methods of implants have been discussed for several decades. The most common fixation method is cementing of the components using polymethyl methacrylate (PMMA).[11, [12, 58] As a consequence, more complex reconstructions may be needed requiring the use of bone grafts or larger implants for revision surgery.[59] Other disadvantages are the production of cement debris, the slow degradation of cement with long-term loosening as consequence and the time needed for cement to harden.[60] Therefore, uncemented fixation has gained interest over the years. Specifically, when using coatings promoting osseointegration. Uncemented fixation allows for a biological fixation of the implant to the bone and preserves bone stock in case of revision surgery.[60, 61] In the last decades, novel designs and implant coatings have been developed to enhance bone ingrowth into the prosthesis in order to provide a long-lasting fixation.[60] Additive technology, also known as 3D-printing, was introduced to further optimize osseointegration as it allows the manufacturing of highly porous implants. These highly porous implants could mimic the stiffness and elasticity of bone and could therefore further augment implant fixation.[62] Uncemented fixation is especially relevant for younger patients as the life-time risk of a TKA revision of these patients is higher compared to the average TKA population.[60, 61, 63, 64] The major drawback of uncemented TKAs in the past was the increased risk of early failure compared with cemented counterparts. However, recent studies no longer show superiority of cemented TKAs over uncemented TKAs in terms of survival or clinical outcomes.[61, 65-67] Despite these promising results, uncemented TKAs account for less than 10% of all TKAs registered in arthroplasty registries.[11, 12, 58]

Evaluation of novel implant designs

Most 50-year-old implant design principles are still valid nowadays. However, minimizing the number of implant designs and sizes is one of the neglected principles while using multiple different implants could be associated with an increased risk of revision [#14, Table I.I].[24,68] TKAs could differ in several characteristics. First, every manufacturer has his own TKA design or several different TKA designs. Second, the fixation method could either be cemented (i.e., cemented femoral and tibial component), hybrid (i.e., cemented femoral and uncemented tibial component or vice versa), or uncemented (i.e., uncemented femoral and tibial component). Further, the constraint could differ between designs (e.g., CR or PS). Also, the tibial component could be MBT or APT. Last, MBT components could have fixed- or mobile-bearing inserts. Every different combination of these characteristics could theoretically influence revision rates and functional outcomes even though the differences between these implant characteristics could be small. A study comparing cemented PS designs to cemented CR designs using data from the Dutch Arthroplasty Registry, for example, found that cemented PS designs were 1.5 times more likely to be revised compared to cemented CR designs.[69]

One could question whether further improvements of TKA designs are needed as revision rates have dropped considerably since the introduction of TKA and are relatively low (i.e., ten-year revision rate 4-6%).[11, 12, 58] While initially a novel design had the potential to significantly reduce the revision rate, the chance of reducing revision rates even further is limited. The evolution of the performance of TKAs in terms of revision rates could be illustrated by a reversed S-curve: an initial slow reduction of revision rate followed by a period of fast reduction [Figure I.I]. After this period, the curve flattens, and further improvements have minimal or even a detrimental effect on the revision rate [Figure I.I].[62] However, a reason to continue innovation of TKA designs could be to increase patient satisfaction. Whereas the revision rates have dropped significantly over the past decades, patient satisfaction trails behind as approximately one in five patient is not satisfied following TKA.[22] Many efforts have been put into understanding the reason for this relatively high rate of unsatisfied patients, but unfortunately, the reasons remain unclear. Hence, novel implant designs have been developed aiming to increase patient satisfaction by, for example,

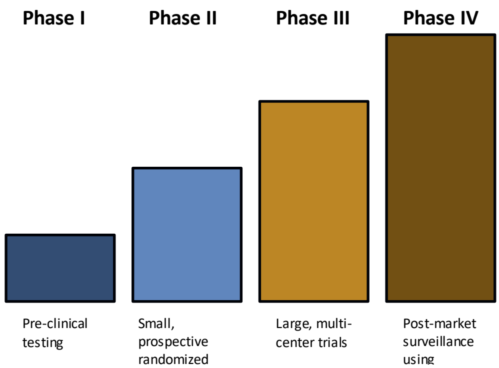
Figure I.I A reversed S-curve illustrating revision rates (y-axis) over time (x-axis).



introducing a mobile-bearing insert or an asymmetrical tibial baseplate to allow more natural movement of the knee joint which in turn could theoretically increase patient satisfaction following TKA.

These novel TKA designs are introduced on a regular basis and often without (sufficient) evidence of lower revision rates or better clinical outcomes compared to their predecessor.[70] An evidence-based approach is needed when introducing novel TKA designs to expose a minimal number of patients to a novel treatment to ensure patient safety. Therefore, several authors suggested the introduction of novel implants in a phased fashion.[6, 71-76] A phased introduction includes several phases which are considered necessary to safely implement novel TKA designs without compromising patient safety [Figure I.II].[6, 71-76] The first phase includes pre-clinical testing which is followed by a phase that should include prospective, randomized controlled clinical trials. These clinical trials preferably include a limited number of patients to minimalize the risks associated with a novel TKA design. Results from phase II could be used to assess whether it is beneficial to continue to phase III. In the next clinical phase (i.e., phase III), large, multicentre studies are conducted to assess whether the novel design improves patient outcomes in a more generic population before this novel implant is widely implemented in clinical practice and is then continued to be monitored for any unintended consequences (as part of post-marketing surveillance). A phased introduction is needed to prevent implant failures which have previously been shown to result in severe patient morbidity.[77, 78]

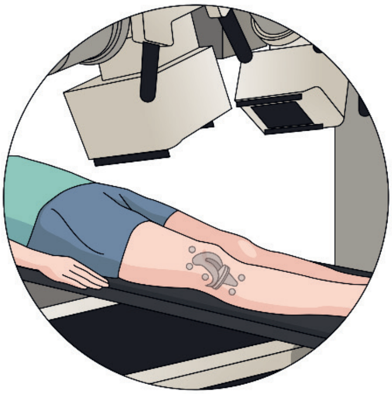
Figure I.II A phased introduction including four steps: 1) pre-clinical testing, 2) small, prospective randomized clinical trials, 3) large, multicentre trials, and 4) post-market surveillance using registries[6]



The role of Radiostereometric Analysis in evaluation of implant designs

Radiostereometric analysis (RSA) is suggested to be implemented as an early detection tool in the first clinical step of a phased implant introduction.[6, 71, 73, 74, 76, 79] The reason for this is that RSA could provide accurate objective results on the performance of novel implants after one or two years. These studies frequently compare well-performing design with a novel design in a randomised trial and it requires only a limited number of approximately 30 patients per treatment arm. RSA uses two 2D radiographs taken in a stereo fashion to reconstruct a 3D image to estimate migration of implants [Figure I.III].[79] RSA calculates the position of the implant by measuring the position of radiopaque tantalum markers, which are inserted in the bone surrounding the implant during surgery, relative to predefined markers positioned on a calibration box.[79] These radiopaque tantalum beads have a varying diameter (0.5-, 0.8-, or 1.0-mm).[79-83] During follow-up visits, the position of the implant relative to the tantalum markers in the bone is again calculated and any change in relative implant position over time is considered to be migration.[79] The position of the implant can be determined by attaching tantalum beads to the implant before surgery, by inserting tantalum beads in the polyethylene (marker-based RSA) or by using a model of the implant (model-based RSA), which has the advantage that it does not require markers in or attached to the implant.[84] The change of implant position is called migration and expressed as translation along or rotation about the transverse, longitudinal, and sagittal axis. Maximum total point motion (MTPM) is used as a summary measure and is an estimate of the length of the translational vector of the point with the greatest

Figure I.III Radiostereometric analysis set-up. Two Rontgen foci are positioned above the knee implant and the knee implant is positioned above a calibration box. Several tantalum beads have been inserted in the tibial bone and/or femoral bone during surgery, and are used to measure migration of the implant.



migration.[85] MTPM is frequently used to assess the stability of an implant and the risk of tibial loosening as an increased MTPM is associated with tibial loosening.[86-88] To assess the risk of tibial failure, certain thresholds have been proposed. First, Ryd et al. (1995) analysed 155 TKAs and unicondylar knee arthroplasties (UKAs), and suggested that implants migrating >0.2 mm were at risk of failure due to aseptic loosening.[86] Approximately 20 years later, Pijls et al. (2012) conducted a meta-analysis of all TKA RSA studies and associated migration found in these RSA studies to five- and ten-year revision rates of the same implants reported in clinical studies and arthroplasty registries.[87] They suggested a classification into three categories according to the extent of migration at one year. The thresholds for these categories were <0.54 mm MTPM (i.e., acceptable), 0.54-1.60 mm MTPM (i.e., at risk), and >1.60 mm MTPM (i.e., unacceptable). TKA designs with a mean migration <0.54 mm migration was considered safe to use and the use of implants with more than 1.60 mm migration should be avoided. Implants with a migration between these two thresholds should be carefully monitored in future studies and clinical practice. Both studies suggested that tibial migration and the risk of failure due to loosening were associated. This makes RSA a very suitable tool to detect any problems early and explains why it is frequently used to compare different TKA designs.

Outline of this thesis

The aim of the present thesis was to contribute to better understand the influence of differences in implant design and surgical techniques on migration of TKA, and more broadly on the effect of using RSA and other markers to detect loosening early.

The association between migration measured with RSA and aseptic loosening is well studied in clinical studies. However, whether TKA designs studies in RSA studies have lower revision rates in arthroplasty registries is unclear. Therefore, **Chapter II** compared the five- and ten-year revision rates of RSA-tested with non-RSA-tested TKAs reported in arthroplasty registries.

Although RSA is an objective method to assess clinical outcome following TKA, a disadvantage of RSA as a diagnostic tool for implant loosening is that it can only be used if RSA markers are inserted during surgery. A few other non-operative markers to identify loosened implants have been described. Having pre-emptive markers of implant loosening could potentially open strategies to not only prevent more severe implant loosening, but also has the potential to monitor disease progression. **Chapter III** aimed to identify the most frequently studied markers which can discriminate between loosened and stable THAs and TKAs, and therefore have the most promising results in differentiating between these groups.

Any change in implant design or surgical technique could potentially have a major impact on revision rates or functional outcomes after TKA. Therefore, **Chapter IV**, **Chapter V**, and **Chapter VI** assessed the effect of two different design changes on migration in a randomized controlled trial using RSA. First, a MBT and APT TKA were compared up to two years in **Chapter IV**. Second, a cemented TKA was compared to a 3D-printed, uncemented TKA in terms of migration in **Chapter V**. Although two-year migration is a commonly used follow-up duration for RSA studies, longer follow-up is needed to determine whether implants showing continuous migration in the second postoperative year continue to migrate or stabilize. The aim of **Chapter VI** was therefore to compare migration up to five years of metal-backed (MBT) and all-polyethylene tibial (APT) components in total knee arthroplasty using a cruciate-stabilising (CS) design in one study and a posterior-stabilising (PS) design in another study. In addition, migration profiles of continuously migrating implants in the second postoperative year were evaluated.

As noted earlier, thresholds in migration have been defined to identify which implants are at risk for loosening. These thresholds have been determined for TKA, while migration patterns of unicondylar knee arthroplasties (UKAs) could be different. Therefore, we evaluated migration patterns of tibial components of UKAs in a meta-analysis (**Chapter VII**).

Beside these implant design characteristics, the surgical technique itself, such as coronal alignment of TKAs, could also have effect on implant migration. Malaligned TKAs have a higher risk of revision, but recent studies have shown ambiguous results regarding the importance of alignment on implant survival and patient satisfaction. Even more, some advocate TKA placement according to the preoperative constitutional aligned limb.[89] For that matter, the effect of alignment on TKA migration was studied, comparing tibial component migration up to two years between 'malaligned' TKAs (i.e. varus or valgus alignment) with aligned TKAs, taking into account the preoperative varus or valgus aligned native knee (**Chapter VIII**).

References

1. Murphy L,Helmick CG. The impact of osteoarthritis in the United States: a population-health perspective: A population-based review of the fourth most common cause of hospitalization in U.S. adults. Orthop Nurs. 2012. 31(2): 85-91.
2. Vitaloni M, Botto-van Bemden A, Sciortino Contreras RM, Scotton D, Bibas M, Quintero M, et al. Global management of patients with knee osteoarthritis begins with quality of life assessment: a systematic review. BMC Musculoskelet Disord. 2019. 20(1): 493.
3. Hunter DJ,Bierma-Zeinstra S. Osteoarthritis. Lancet. 2019. 393(10182): 1745-1759.
4. Vos T, Flaxman AD, Naghavi M, Lozano R, Michaud C, Ezzati M, et al. Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet. 2012. 380(9859): 2163-96.
5. Wallace IJ, Worthington S, Felson DT, Jurmain RD, Wren KT, Maijanen H, et al. Knee osteoarthritis has doubled in prevalence since the mid-20th century. Proc Natl Acad Sci U S A. 2017. 114(35): 9332-9336.
6. Malchau H. On the importance of stepwise introduction of new hip implant technology: Assessment of total hip replacement using clinical evaluation, radiostereometry, digitized radiography and a national hip registry [Thesis]. Göteborg, Sweden: Göteborg University. 1995.
7. National institute for health and care excellence (NICE),. Osteoarthritis: Care and management. 'Available from:' https://www.nice.org.uk/guidance/cg177/resources/osteoarthritis-care-and-management-pdf-35109757272517. Accessed on February 11th, 2021.
8. Bachmeier CJ, March LM, Cross MJ, Lapsley HM, Tribe KL, Courtenay BG, et al. A comparison of outcomes in osteoarthritis patients undergoing total hip and knee replacement surgery. Osteoarthritis Cartilage. 2001. 9(2): 137-46.
9. Keurentjes JC, Fiocco M, So-Osman C, Onstenk R, Koopman-Van Gemert AW, Pöll RG, et al. Patients with severe radiographic osteoarthritis have a better prognosis in physical functioning after hip and knee replacement: a cohort-study. PLoS One. 2013. 8(4): e59500.
10. Beswick AD, Wylde V, Gooberman-Hill R, Blom A,Dieppe P. What proportion of patients report long-term pain after total hip or knee replacement for osteoarthritis? A systematic review of prospective studies in unselected patients. BMJ Open. 2012. 2(1): e000435.
11. LROI, Dutch Artrhoplasty Register. Online LROI annual report 2020. 'Available from:' https://www.lroi-report.nl/. Accessed on 11-03-2021.
12. SKAR SKAR. Annual report 2020. 'Available from:' http://myknee.se/pdf/SVK_2020_Eng_1.0.pdf. Accessed on April 12, 2021.
13. LROI, Dutch Artrhoplasty Register. Online LROI annual report 2022. 'Available from:' www.lroi-report.nl Accessed
14. Otten R, van Roermund PM,Picavet HS. [Trends in the number of knee and hip arthroplasties: considerably more knee and hip prostheses due to osteoarthritis in 2030]. Ned Tijdschr Geneeskd. 2010. 154: A1534.
15. Kurtz S, Ong K, Lau E, Mowat F,Halpern M. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. J Bone Joint Surg Am. 2007. 89(4): 780-5.
16. Ackerman IN, Bohensky MA, Zomer E, Tacey M, Gorelik A, Brand CA, et al. The projected burden of primary total knee

and hip replacement for osteoarthritis in Australia to the year 2030. BMC Musculoskelet Disord. 2019. 20(1): 90.
17. Inacio MCS, Graves SE, Pratt NL, Roughead EE,Nemes S. Increase in Total Joint Arthroplasty Projected from 2014 to 2046 in Australia: A Conservative Local Model With International Implications. Clin Orthop Relat Res. 2017. 475(8): 2130-2137.
18. Rupp M, Lau E, Kurtz SM,Alt V. Projections of Primary TKA and THA in Germany From 2016 Through 2040. Clin Orthop Relat Res. 2020. 478(7): 1622-1633.
19. Nemes S, Gordon M, Rogmark C,Rolfson O. Projections of total hip replacement in Sweden from 2013 to 2030. Acta Orthop. 2014. 85(3): 238-43.
20. Kumar A, Tsai WC, Tan TS, Kung PT, Chiu LT,Ku MC. Temporal trends in primary and revision total knee and hip replacement in Taiwan. J Chin Med Assoc. 2015. 78(9): 538-44.
21. Maradit Kremers H, Larson DR, Crowson CS, Kremers WK, Washington RE, Steiner CA, et al. Prevalence of Total Hip and Knee Replacement in the United States. J Bone Joint Surg Am. 2015. 97(17): 1386-97.
22. Bourne RB, Chesworth BM, Davis AM, Mahomed NN,Charron KD. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? Clin Orthop Relat Res. 2010. 468(1): 57-63.
23. Nilsdotter AK,Isaksson F. Patient relevant outcome 7 years after total hip replacement for OA - a prospective study. BMC Musculoskelet Disord. 2010. 11: 47.
24. Mariconda M, Galasso O, Costa GG, Recano P,Cerbasi S. Quality of life and functionality after total hip arthroplasty: a long-term follow-up study. BMC Musculoskelet Disord. 2011. 12: 222.
25. Keurentjes JC, Blane D, Bartley M, Keurentjes JJ, Fiocco M,Nelissen RG. Socio-economic position has no effect on improvement in health-related quality of life and patient satisfaction in total hip and knee replacement: a cohort study. PLoS One. 2013. 8(3): e56785.
26. Keurentjes JC, Van Tol FR, Fiocco M, Schoones JW,Nelissen RG. Minimal clinically important differences in health-related quality of life after total hip or knee replacement: A systematic review. Bone Joint Res. 2012. 1(5): 71-7.
27. Keurentjes JC, Fiocco M,Nelissen RG. Willingness to undergo surgery again validated clinically important differences in health-related quality of life after total hip replacement or total knee replacement surgery. J Clin Epidemiol. 2014. 67(1): 114-20.
28. Keurentjes JC, Van Tol FR, Fiocco M, So-Osman C, Onstenk R, Koopman-Van Gemert AW, et al. Patient acceptable symptom states after totalhip or knee replacement at mid-term follow-up: Thresholds of the Oxford hip and knee scores. Bone Joint Res. 2014. 3(1): 7-13.
29. Peter WF, Dekker J, Tilbury C, Tordoir RL, Verdegaal SH, Onstenk R, et al. The association between comorbidities and pain, physical function and quality of life following hip and knee arthroplasty. Rheumatol Int. 2015. 35(7): 1233-41.
30. Tilbury C, Haanstra TM, Verdegaal SHM, Nelissen R, de Vet HCW, Vliet Vlieland TPM, et al. Patients' pre-operative general and specific outcome expectations predict postoperative pain and function after total knee and total hip arthroplasties. Scand J Pain. 2018. 18(3): 457-466.
31. Loef M, Gademan MGJ, Latijnhouwers D, Kroon HM, Kaptijn HH, Marijnissen W, et al. Comparison of KOOS Scores of Middle-Aged Patients Undergoing Total Knee Arthroplasty to the General Dutch Population Using KOOS Percentile Curves: The LOAS Study. J Arthroplasty. 2021. 36(8): 2779-2787.e4.
32. Freeman MA, Swanson SA,Todd RC. Total replacement of the knee using the Freeman-Swanson knee prosthesis. Clin Orthop Relat Res. 1973(94): 153-70.
33. Insall J, Ranawat CS, Scott WN,Walker P. Total condylar knee replacment: preliminary report. Clin Orthop Relat Res. 1976(120): 149-54.

34. Coventry MB, Finerman GA, Riley LH, Turner RH,Upshaw JE. A new geometric knee for total knee arthroplasty. Clin Orthop Relat Res. 1972. 83: 157-62.
35. Ranawat CS, Insall J,Shine J. Duo-condylar knee arthroplasty: hospital for special surgery design. Clin Orthop Relat Res. 1976(120): 76-82.
36. Ducheyne P, Kagan A, 2nd,Lacey JA. Failure of total knee arthroplasty due to loosening and deformation of the tibial component. J Bone Joint Surg Am. 1978. 60(3): 384-91.
37. Skolnick MD, Coventry MB,Ilstrup DM. Geometric total knee arthroplasty. A two-year follow-up study. J Bone Joint Surg Am. 1976. 58(6): 749-53.
38. Robinson RP. The early innovators of today's resurfacing condylar knees. J Arthroplasty. 2005. 20(1 Suppl 1): 2-26.
39. Steinberg DR,Steinberg ME. The early history of arthroplasty in the United States. Clin Orthop Relat Res. 2000(374): 55-89.
40. Browne JA, Gall Sims SE, Giuseffi SA,Trousdale RT. All-polyethylene tibial components in modern total knee arthroplasty. J Am Acad Orthop Surg. 2011. 19(9): 527-35.
41. Bartel DL, Burstein AH, Santavicca EA,Insall JN. Performance of the tibial component in total knee replacement. J Bone Joint Surg Am. 1982. 64(7): 1026-33.
42. Lewis JL, Askew MJ,Jaycox DP. A comparative evaluation of tibial component designs of total knee prostheses. J Bone Joint Surg Am. 1982. 64(1): 129-35.
43. Reilly D, Walker PS, Ben-Dov M,Ewald FC. Effects of tibial components on load transfer in the upper tibia. Clin Orthop Relat Res. 1982(165): 273-82.
44. Doran J, Yu S, Smith D,Iorio R. The Role of All-Polyethylene Tibial Components in Modern TKA. J Knee Surg. 2015. 28(5): 382-9.
45. Gustke KA,Gelbke MK. All-Polyethylene Tibial Component Use for Elderly, Low-Demand Total Knee Arthroplasty Patients. J Arthroplasty. 2017. 32(8): 2421-2426.
46. Gioe TJ,Maheshwari AV. The all-polyethylene tibial component in primary total knee arthroplasty. J Bone Joint Surg Am. 2010. 92(2): 478-87.
47. Brown TS, Van Citters DW, Berry DJ,Abdel MP. The use of highly crosslinked polyethylene in total knee arthroplasty. Bone Joint J. 2017. 99-b(8): 996-1002.
48. Orita K, Minoda Y, Sugama R, Ohta Y, Ueyama H, Takemura S, et al. Vitamin E-infused highly cross-linked polyethylene did not reduce the number of in vivo wear particles in total knee arthroplasty. Bone Joint J. 2020. 102-b(11): 1527-1534.
49. Takemura S, Minoda Y, Sugama R, Ohta Y, Nakamura S, Ueyama H, et al. Comparison of a vitamin E-infused highly crosslinked polyethylene insert and a conventional polyethylene insert for primary total knee arthroplasty at two years postoperatively. Bone Joint J. 2019. 101-b(5): 559-564.
50. Lachiewicz PF,O'Dell JA. Prospective randomized trial of standard versus highly crosslinked tibial polyethylene in primary posterior-stabilized total knee arthroplasty: clinical and radiological follow-up at 2 to 11 years. Bone Joint J. 2019. 101-b(7_Supple_C): 33-39.
51. Meneghini RM, Ireland PH,Bhowmik-Stoker M. Multicenter Study of Highly Cross-linked vs Conventional Polyethylene in Total Knee Arthroplasty. J Arthroplasty. 2016. 31(4): 809-14.
52. Meneghini RM, Lovro LR, Smits SA,Ireland PH. Highly Cross-Linked Versus Conventional Polyethylene in Posterior-Stabilized Total Knee Arthroplasty at a Mean 5-Year Follow-up. J Arthroplasty. 2015. 30(10): 1736-9.
53. Kindsfater KA, Pomeroy D, Clark CR, Gruen TA, Murphy J,Himden S. In Vivo Performance of Moderately Crosslinked, Thermally Treated Polyethylene in a Prospective Randomized Controlled

Primary Total Knee Arthroplasty Trial. J Arthroplasty. 2015. 30(8): 1333-8.
54. Paxton EW, Inacio MC, Kurtz S, Love R, Cafri G,Namba RS. Is there a difference in total knee arthroplasty risk of revision in highly crosslinked versus conventional polyethylene? Clin Orthop Relat Res. 2015. 473(3): 999-1008.
55. Partridge TCJ, Baker PN, Jameson SS, Mason J, Reed MR,Deehan DJ. Conventional Versus Highly Cross-Linked Polyethylene in Primary Total Knee Replacement: A Comparison of Revision Rates Using Data from the National Joint Registry for England, Wales, and Northern Ireland. J Bone Joint Surg Am. 2020. 102(2): 119-127.
56. Boyer B, Bordini B, Caputo D, Neri T, Stea S,Toni A. Is Cross-Linked Polyethylene an Improvement Over Conventional Ultra-High Molecular Weight Polyethylene in Total Knee Arthroplasty? J Arthroplasty. 2018. 33(3): 908-914.
57. de Steiger RN, Muratoglu O, Lorimer M, Cuthbert AR,Graves SE. Lower prosthesis-specific 10-year revision rate with crosslinked than with non-crosslinked polyethylene in primary total knee arthroplasty. Acta Orthop. 2015. 86(6): 721-7.
58. NJR NJR. 17th Annual Report 2020. 'Available from:' https://reports.njrcentre.org.uk/Portals/0/PDFdownloads/NJR%2017th%20Annual%20Report%202020.pdf. Accessed on 08-02-2021.
59. Panegrossi G, Ceretti M, Papalia M, Casella F, Favetti F,Falez F. Bone loss management in total knee revision surgery. Int Orthop. 2014. 38(2): 419-27.
60. Dalury DF. Cementless total knee arthroplasty: current concepts review. Bone Joint J. 2016. 98-b(7): 867-73.
61. Meneghini RM,Hanssen AD. Cementless fixation in total knee arthroplasty: past, present, and future. J Knee Surg. 2008. 21(4): 307-14.
62. Mumith A, Thomas M, Shah Z, Coathup M,Blunn G. Additive manufacturing: current concepts, future trends. Bone Joint J. 2018. 100-b(4): 455-460.
63. Bayliss LE, Culliford D, Monk AP, Glyn-Jones S, Prieto-Alhambra D, Judge A, et al. The effect of patient age at intervention on risk of implant revision after total replacement of the hip or knee: a population-based cohort study. Lancet. 2017. 389(10077): 1424-1430.
64. Gademan MGJ, Van Steenbergen LN, Cannegieter SC, Nelissen R,Marang-Van De Mheen PJ. Population-based 10-year cumulative revision risks after hip and knee arthroplasty for osteoarthritis to inform patients in clinical practice: a competing risk analysis from the Dutch Arthroplasty Register. Acta Orthop. 2021. 92(3): 280-284.
65. Hu B, Chen Y, Zhu H, Wu H,Yan S. Cementless Porous Tantalum Monoblock Tibia vs Cemented Modular Tibia in Primary Total Knee Arthroplasty: A Meta-Analysis. J Arthroplasty. 2017. 32(2): 666-674.
66. Mont MA, Pivec R, Issa K, Kapadia BH, Maheshwari A,Harwin SF. Long-term implant survivorship of cementless total knee arthroplasty: a systematic review of the literature and meta-analysis. J Knee Surg. 2014. 27(5): 369-76.
67. Zhou K, Yu H, Li J, Wang H, Zhou Z,Pei F. No difference in implant survivorship and clinical outcomes between full-cementless and full-cemented fixation in primary total knee arthroplasty: A systematic review and meta-analysis. Int J Surg. 2018. 53: 312-319.
68. Penfold CM, Whitehouse MR, Sayers A, Wilkinson JM, Hunt L, Ben-Shlomo Y, et al. A Comparison of the Surgical Practice of Potential Revision Outlier Joint Replacement Surgeons With Non-outliers: A Case Control Study From the National Joint Registry for England, Wales, Northern Ireland and the Isle of Man. J Arthroplasty. 2021. 36(4): 1239-1245.e6.
69. Spekenbrink-Spooren A, Van Steenbergen LN, Denissen GAW, Swierstra BA,

Poolman RW,Nelissen R. Higher mid-term revision rates of posterior stabilized compared with cruciate retaining total knee arthroplasties: 133,841 cemented arthroplasties for osteoarthritis in the Netherlands in 2007-2016. Acta Orthop. 2018. 89(6): 640-645.
70. Nieuwenhuijse MJ, Nelissen RG, Schoones JW,Sedrakyan A. Appraisal of evidence base for introduction of new implants in hip and knee replacement: a systematic review of five widely used device technologies. Bmj. 2014. 349: g5133.
71. Faro LM,Huiskes R. Quality assurance of joint replacement. Legal regulation and medical judgement. Acta Orthop Scand Suppl. 1992. 250: 1-33.
72. Hirst A, Philippou Y, Blazeby J, Campbell B, Campbell M, Feinberg J, et al. No Surgical Innovation Without Evaluation: Evolution and Further Development of the IDEAL Framework and Recommendations. Ann Surg. 2019. 269(2): 211-220.
73. Nelissen RG, Pijls BG, Karrholm J, Malchau H, Nieuwenhuijse MJ,Valstar ER. RSA and registries: the quest for phased introduction of new implants. J Bone Joint Surg Am. 2011. 93: 62-5.
74. Nieuwenhuijse MJ,Nelissen RG. [The introduction of new medical devices] [In Dutch]. Ned Tijdschr Geneeskd. 2015. 159: A8652.
75. Sedrakyan A, Campbell B, Merino JG, Kuntz R, Hirst A,McCulloch P. IDEAL-D: a rational framework for evaluating and regulating the use of medical devices. Bmj. 2016. 353: i2372.
76. Pijls BG,Nelissen RG. The era of phased introduction of new implants. Bone Joint Res. 2016. 5(6): 215-7.
77. Heneghan C, Langton D,Thompson M. Ongoing problems with metal-on-metal hip implants. Bmj. 2012. 344: e1349.
78. Rising JP, Reynolds IS,Sedrakyan A. Delays and difficulties in assessing metal-on-metal hip implants. N Engl J Med. 2012. 367(1): e1.
79. Selvik G. Roentgen stereophotogrammetry. A method for the study of the kinematics of the skeletal system. Acta Orthop Scand Suppl. 1989. 232: 1-51.
80. van Hamersveld KT, Marang-van de Mheen PJ, Koster LA, Nelissen R, Toksvig-Larsen S,Kaptein BL. Marker-based versus model-based radiostereometric analysis of total knee arthroplasty migration: a reanalysis with comparable mean outcomes despite distinct types of measurement error. Acta Orthop. 2019. 90(4): 366-372.
81. Dunbar MJ, Wilson DA, Hennigar AW, Amirault JD, Gross M,Reardon GP. Fixation of a trabecular metal knee arthroplasty component. A prospective randomized study. J Bone Joint Surg Am. 2009. 91(7): 1578-86.
82. Stilling M, Mechlenburg I, Jepsen CF, Rømer L, Rahbek O, Søballe K, et al. Superior fixation and less periprosthetic stress-shielding of tibial components with a finned stem versus an I-beam block stem: a randomized RSA and DXA study with minimum 5 years' follow-up. Acta Orthop. 2019. 90(2): 165-171.
83. Callary SA, Campbell DG, Mercer G, Nilsson KG,Field JR. Wear of a 5 megarad cross-linked polyethylene liner: a 6-year RSA study. Clin Orthop Relat Res. 2013. 471(7): 2238-44.
84. Kaptein BL, Valstar ER, Stoel BC, Rozing PM,Reiber JH. A new model-based RSA method validated using CAD models and models from reversed engineering. J Biomech. 2003. 36(6): 873-82.
85. ISO16087:2013(E). Implants for surgery: Roentgen stereophotogrammetric analysis for the assessment of migration of orthopaedic implants. Geneva, Switzerland: International Organization for Standardization. 2013.
86. Ryd L, Albrektsson BE, Carlsson L, Dansgard F, Herberts P, Lindstrand A, et al. Roentgen stereophotogrammetric analysis as a predictor of mechanical

loosening of knee prostheses. J Bone Joint Surg Br. 1995. 77(3): 377-83.
87. Pijls BG, Valstar ER, Nouta KA, Plevier JW, Fiocco M, Middeldorp S, et al. Early migration of tibial components is associated with late revision: a systematic review and meta-analysis of 21,000 knee arthroplasties. Acta Orthop. 2012. 83(6): 614-24.
88. Pijls BG, Plevier JWM,Nelissen R. RSA migration of total knee replacements. Acta Orthop. 2018: 1-9.
89. Bellemans J, Colyn W, Vandenneucker H,Victor J. The Chitranjan Ranawat award: is neutral mechanical alignment normal for all patients? The concept of constitutional varus. Clin Orthop Relat Res. 2012. 470(1): 45-53.