International Orthopaedics (2019) 43:597–604
https://doi.org/10.1007/s00264-018-3913-z

REVIEW ARTICLE

Total knee arthroplasties from the origin to navigation: history, rationale, indications

Dominique Saragaglia[1] · Brice Rubens-Duval[1] · Julia Gaillot[1] · Gabriel Lateur[1] · Régis Pailhé[1]

Received: 30 December 2017 / Accepted: 16 March 2018 / Published online: 27 March 2018

Abstract

Since the early 1970s, total knee arthroplasties have undergone many changes in both their design and their surgical instrumentation. It soon became apparent that to improve prosthesis durability, it was essential to have instruments which allowed them to be fitted reliably and consistently. Despite increasingly sophisticated surgical techniques, preoperative objectives were only met in 75% of cases, which led to the development, in the early 1990s, in Grenoble (France), of computer-assisted orthopaedic surgery for knee prosthesis implantation. In the early 2000s, many navigation systems emerged, some including pre-operative imagery ("CT-based"), others using intra-operative imagery ("fluoroscopy-based"), and yet others with no imagery at all ("imageless"), which soon became the navigation "gold standard". They use an optoelectronic tracker, markers which are fixed solidly to the bones and instruments, and a navigation workstation (computer), with a control system (e.g. pedal). Despite numerous studies demonstrating the benefit of computer navigation in meeting preoperative objectives, such systems have not yet achieved the success they warrant, for various reasons we will be covering in this article. If the latest navigation systems prove to be as effective as the older systems, they should give this type of technology a well-deserved boost.

Keywords Knee · Osteoarthritis · Arthroplasty · Navigation · Computer

Introduction

The first attempts at knee replacements date back to the late nineteenth century (Gluck). The materials used (ivory in the case of Gluck's prosthesis) and the antiseptic conditions meant that only sporadic trials were carried out. Many other attempts were made up until the 1950s, although, sadly, most failed in the very early stages [in 1]. The "modern" period started with the launch in 1954 of hinged prostheses (Walldius, Shiers) and, later, the Guépar prosthesis [2] in 1970. The principles of these prostheses were improved, introducing a certain degree of rotation between the femoral and tibial implants [3], which led to the rotating-hinged prostheses still in use today. Gunston [4] was the first to promote gliding prostheses, between 1965 and 1968, with a metal femoral component gliding on a polyethylene tibial platform. Marmor [5] applied this principal to unicompartmental prostheses from the early 1970s. Today, gliding prostheses exist in many forms. One distinguishes unicompartmental prostheses with either a fixed bearing plateau, derived from Marmor's prosthesis, with a metal or full-poly tibial platform, or a mobile-bearing plateau—a concept initiated in 1978 [6]. Then total prostheses, which can be categorised according to whether the posterior cruciate ligaments are retained or not, and whether they include a fixed bearing or rotating platform. Prostheses preserving both cruciate ligaments [7] are no longer used, although several manufacturers are currently trying to relaunch this concept. Cruciate retaining (CR) prostheses are widely used, throughout the world, although there has recently been a clear rise in the use of posterior-stabilised (PS) prostheses, which involve removal of the posterior cruciate ligament. The development of

✉ Dominique Saragaglia
DSaragaglia@chu–grenoble.fr

Brice Rubens-Duval
BRubensduval@chu-grenoble.fr

Julia Gaillot
gaillot.julia@gmail.com

Gabriel Lateur
GLateur@chu-grenoble.fr

Régis Pailhé
RPailhe@chu-grenoble.fr

[1] Department of Orthopaedic Surgery and Sport Traumatology, Grenoble South Teaching Hospital, 38130 Échirolles, France

posterior stabilisation, in the early 1980s [8], contributed to the development of this type of implant, with either a central cam, or with a third condyle. The mobile-bearing total prosthesis was born in the late 1970s [9] under the name LCS prosthesis, with the aim of reducing certain constraints between the femoral implant and the tibial platform. In the late 1990s, numerous other mobile-bearing prostheses were developed in an attempt to reduce wear, osteolysis and loosening. These prostheses' main principle was to maximise congruence between the condyle and the polyethylene [10–12] and most had a rotating platform, although there are models with anteroposterior and mediolateral mobility combined with the rotating platform [13]. In the past few years, prostheses have been launched offering improved knee flexion and which are referred to as "High Flexion" [14]; others are referred to as ultra-congruent, as they reduce wear to the polyethylene [15] whilst others, offering different sizes for men and women, are referred to as "Gender specific Knees" [16].

Alongside the development of these prostheses, the instrumentation has also been improved, to allow optimal implantation of the prostheses, i.e. perpendicular to the mechanical axis of the lower limb, to improve their lifespan by avoiding early wear and loosening. In the early 1970s, the instrumentation was rather rudimentary and it quickly became apparent that guides were needed to ensure correct alignment of prostheses in the sagittal and frontal planes [17]. The extramedullary femoral rod was quickly replaced by the intramedullary rod, which is still the reference today. The extramedullary tibial rod is probably the most widely used; however, intramedullary guides do exist, as well as guides which combine intra- and extramedullary rods. Despite their sophistication, these instruments are not infallible and it is not rare for even experienced surgeons to position prostheses with excess valgus or varus (over 5°), or an excessive posterior or anterior tibial slope.

The move to navigation

Numerous historical studies [18–26] have shown that faulty alignment, outside the range of 180°+/−3°, reduces the lifespan of a knee prosthesis. Based on this observation, we determined that traditional instrumentation was insufficient to ensure that pre-operative objectives were met and, as early as 1993, we started to turn to computer navigation for knee replacement surgery. In 1996, after 3 years of research, this navigation system was validated in cadavers, without the use of pre-operative imagery [27, 28]. The principle is based on intra-operative identification of the centre of the femoral head, the centre of the knee and the centre of the ankle, providing real-time front and lateral views of the mechanical axis of the lower limb, on a control screen. The implant is positioned based on these axes, using markers and a Polaris infrared tracker (Northern Digital Inc.).

After obtaining consent from the local ethics committee on December 4, 1996, the first computer-assisted prosthesis was implanted in a patient, on January 21, 1997 (D. Saragaglia, F. Picard, T. Lebredonchel). The operation lasted two hours and 15 minutes and was uneventful. A prospective randomised study comparing this technique to the conventional technique began in January 1998 and was completed in March 1999. The results were published in several national and international meetings and in a lead article in the French Journal of Orthopaedic Surgery [29]. In March 1999, the prototype that we had used in this study evolved to a final model called Orthopilot™ (B-Braun-Aesculap, Tuttlingen, Germany). Since that time, numerous papers have been published confirming that this technique was well founded, and more than 360,000 prostheses have been implanted worldwide using this device. The software packages have evolved (versions 3.0, 3.2, 4.0, 4.2, 5.0, 5.1) but the basic principle has remained the same since the system was created. Today, in our hands, the surgical procedure lasts between one and 1.5 hours, depending on the difficulty of the case, and almost 4000 TKAs have been implanted in our department, using navigation.

The system was rapidly adopted for osteotomies around the knee [30–32] as well as the implantation of unicompartmental prostheses [33, 34], and their revision using total knee prostheses [34].

Other navigation systems and literature review

In the early 2000s, other navigation systems were launched—some pre-operative CT-based (Navitrack™ [35] and VectorVision™ from BrainLAB [36]), others imageless (Stryker Knee Trac [37], CT-Free VectorVision™ from BrainLAB [38] and the Surgetics™ system [39]), whilst yet others used intra-operative fluoroscopy (Medtronic's "Viking" system [40] and Fluoro Knee system from Smith and Nephew and Medtronic [41]). All these systems have now reached maturity and the most widely used are the imageless systems, although the overall use of navigation remains relatively modest and varies greatly between countries (20% in Germany and Australia, 10% in France and 2 to 5% in the UK and the USA). The objectives which led to the development of navigation have been met and have been validated by numerous studies [42–45]. Navigation indisputably offers better frontal and sagittal alignment of prostheses, and facilitates improved ligament balancing [46], although a few isolated studies found it did not improve precision in prosthesis implantation [47, 48]. The functional results [49] and lifespan could be improved, as shown in the Australian register of knee prostheses [50], but there are currently few studies available on this subject [13, 51, 52].

Which navigation system to choose?

When we developed the Orthopilot™ system, our aim was to provide a simple, user-friendly system, with no preoperative CT scan—to reduce cost, irradiation and time wasting both pre- and intra-operatively. Operating times were not to exceed two hours, with an increase in operating time of 10% maximum, if possible. This led us to opt for a kinematic system, based on intra-operative acquisition of identifiable anatomical landmarks [29, 53].

Whatever the system used, in order to navigate successfully, a tracker is required (Fig. 1) to monitor the movements of the limb segments, or the location of the instruments. To be trackable, these objects or limb segments must be fitted with markers which emit a signal recognised by the tracker. The most widely used system is the optoelectronic system, with infrared diode markers and a tracker with two or three CCD cameras. Active markers are usually linked to the camera via a cable (although they can be battery-powered) and produce their own signal, whilst passive markers (Figs. 2 and 3) are completely wireless and use tiny spheres to reflect the light from an emitter on the camera. The advantage of this type of system is that there are no wires in the sterile field, which can be inconvenient for less experimented practitioners, whilst their disadvantage is a lack of precision if one or more of the beads becomes soiled (with blood). Magnetic detection systems have been temporarily abandoned, due to possible interference with metallic or electronic objects, which are commonly found in operating rooms.

Fig. 1 Orthopilot™ Navigator with infrared tracker and computer touch screen

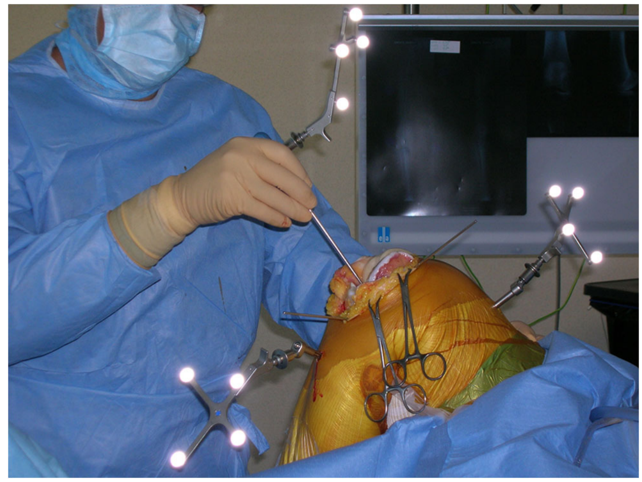

Fig. 2 Light-reflecting passive markers

A computer is also necessary to integrate (Fig. 1), transform and transpose the signals from the markers, using a graphic interface, producing both pictures and quantitative data (such as HKA angle). The computer also enables the surgeon to manage the different stages of the surgical procedure and to check the lower limb mechanical axis, in real time, before positioning the prosthesis, during the operation, and at the end of the procedure. It also allows the ligament balance to be checked, compared with the mechanical axis, and essential data regarding the operation to be recorded.

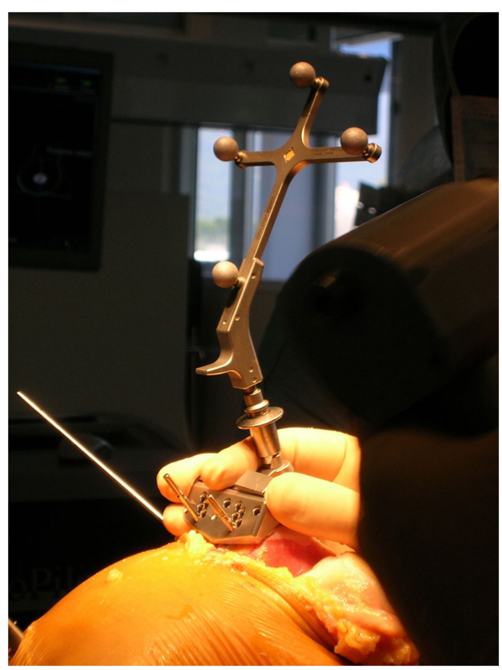

Fig. 3 Distal femoral cutting guide, fitted with marker

Fig. 4 Gonarthrosis on severe genu varum

Finally, a command system is required—either a touch screen (which can be covered with a sterile transparent film) or, preferably, a control pedal used directly by the surgeon.

Navigation systems based on pre-operative imagery use a CT scan produced in the days leading up to the operation and provide a 3-D reproduction of the entire lower limb. Stacked slices of the entire limb must be taken, from hip to ankle, measuring 1 mm around the knee, 3 mm around the hip and ankle and 1 cm along the diaphysis—all of which takes approximately 20 min to obtain [35]. Data is recorded onto a CD-ROM or other support and transferred to the navigation console. Before the operation, the surgeon generally spends 30 to 45 minutes on the computer, planning the operation. The advantages of using a CT scan are the 3D reconstruction of the entire limb, and the ability to measure distal femoral torsion, on condition that this measurement is reliable and reproducible, at least in tracking the bi-epicondylar axis. Disadvantages include the use of a relatively expensive examination, which is not usually part of the standard pre-operative work-up for knee replacement. This means additional cost, additional irradiation and a relatively long and fastidious preoperative planning session.

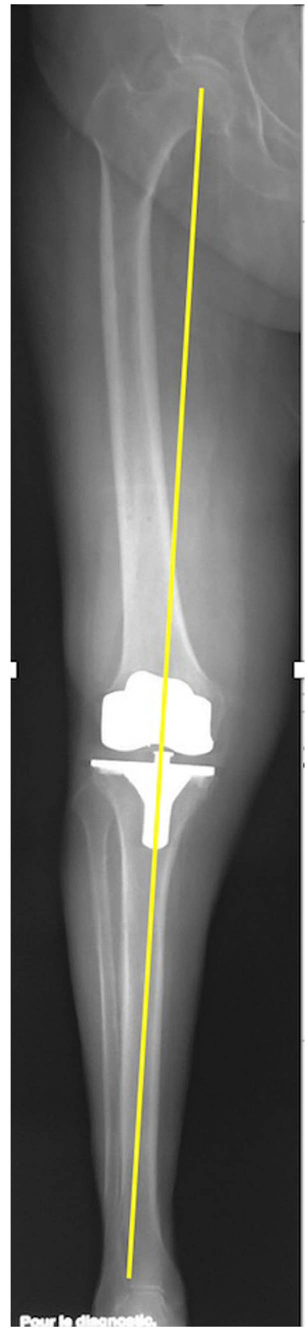

Fig. 5 TKR following navigation of the case in Fig. 4

Navigation using intra-operative fluoroscopy is relatively rare, due to the space it takes up in the operating room,

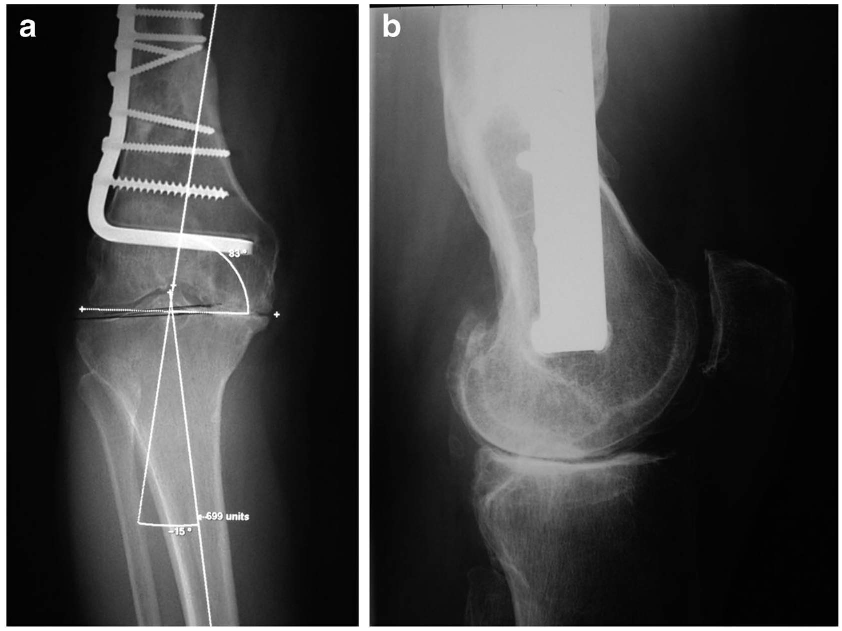

Fig. 6 Gonarthrosis on severe genu varum, recurvatum malunion and 20-year-old screwed plate. **a** Frontal x-ray. **b** Lateral x-ray

the theoretical increase in infectious complications and surgeons not being used to using an image intensifier in prosthetic surgery.

Fig. 7 Post-operative x-ray of the case in Fig. 6. **a** AP goniometry. **b** Lateral view

As mentioned above, the most commonly used systems are those which are imageless, all of which are currently very similar, and which have proven to be effective and reproducible by any user. Over recent years, other navigation systems have appeared on the market. Some are based on accelerometric principles, such as the iAssist navigation system [54, 55] or the OrthAlign navigation system [56], others on the iPod principle [57] whilst others no longer use bone marker fixation [58]. The initial results are promising, but further studies are required to prove any superiority of these new technologies.

Discussion

Computer navigation in knee replacement surgery has reached maturity, but it should be recognised that it has not achieved the degree of development it deserved. The reasons for this lack of enthusiasm are multiple: the complexity of certain navigation systems which emerged in the early 2000s [39] which added over 30 minutes to the operating time; the cost of the equipment at the time, when it had to be bought or rented; the lack of long-term studies proving increased survival of navigated implants; a certain confusion regarding the objectives of navigation, which is not just a tool for implanting prostheses at 180 +/− 3°, but according to the axis chosen, whether anatomical or kinematic [59], with increased precision and greater reproducibility.

It is important to recognise that there are close to zero complications linked to navigation—far fewer than with traditional techniques—in terms of fat embolisms and post-operative bleeding [60, 61]. Also, the learning curve is fast and it is a remarkable tool for teaching knee replacement surgery [62].

The major advantage of navigation is its usefulness in major knee deformities, whether varus (Figs. 4 and 5) or valgus. In this context, it allows pre-operative objectives to be met in over 90% of cases [13], and thanks to its evaluation of the reducibility of the deformity [63], it considerably reduces the major release rate, which is only 9.5% in a recent series [13]. It is also of particular interest for evaluating sagittal ligament balance in the knee, as it is always difficult intra-operatively, to evaluate visually the degree of flexum or residual recurvatum, which navigation can quantify precisely, in degrees.

Finally—and this is certainly one of its major benefits—navigation allows knee replacement to be carried out in excellent conditions in cases of gonarthrosis with femoral or tibial bone malunion, and especially where non-removable osteosyntheses hardware (particularly femoral) are in place [64–66]. The presence of this type of hardware (plates or nails) makes impossible to use an intramedullary rod, which makes surgery riskier (Figs. 6a, b and 7a, b).

Thus, given the many advantages of navigation, rather than using it for special cases, it is preferable to use it routinely, thereby avoiding having to face combining a difficult operation with an unfamiliar surgical technique.

Conclusion

Computer navigation in knee replacement surgery has not achieved the success it deserved, despite having reached maturity and enabling any pre-operative objectives (normal axis, slight varus or slight valgus) to be achieved with ease. The new navigation systems are cheaper, less invasive and faster to use and will undoubtedly give this technology a major boost, if they are as effective as the gold standard represented by the optoelectronic systems with no pre-operative imagery.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent Not applicable.

References

1. Aubriot JH (1989) historique et évolution des prothèses totales du genou. Cahier d'enseignement de la SOFCOT n°35. Expans Sci Fr Paris 189:4
2. Aubriot JH, Deburge A, Kenesi CL, Schramm P (1973) La prothèse Guépar. Acta Orthop Belg 39:257–279
3. Trillat A, Dejour H, Bousquet G, Grammont P (1973) La prothèse rotatoire du genou. Rev Chir Orthop Reparatrice Appar Mot 59: 513–522
4. Gunston FH (1971) Polycentric knee arthroplasty. J Bone Joint Surg Br 53:272–277
5. Marmor L (1973) The modular knee. Clin Orthop Relat Res 94: 242–248
6. Goodfellow J, O'Connor J (1978) The mechanics of the knee and prosthesis design. J Bone Joint Surg Br 60:358–369
7. Cloutier JM (1983) Results of total knee arthroplasty with a non-constrained prosthesis. J Bone Joint Surg Am 65:906–919
8. Insall J, Lachiewicz PF, Burnstein AH (1982) The posterior stabilized condylar prosthesis: a modification of the total condylar design. Two to four-year clinical experience. J Bone Joint Surg Am 64:1317–1323
9. Buechel FF, Pappas MJ (1986) The New Jersey Low-Contact-Stress Knee Replacement System: biomechanical rationale and review of the first 123 cemented cases. Arch Orthop Trauma Surg 105:197–204
10. Argenson JN, Parratte S, Ashour A, Saintmard B, Aubaniac JM (2012) The outcome of rotating-platform total knee arthroplasty with cement at a minimum of ten years of follow-up. J Bone Joint Surg Am 94:638–644
11. Bercovy M, Langlois J, Beldame J, Lefebvre B (2015) Functional results of the ROCC® Mobile Bearing Knee. 602 cases at midterm follow-up (5 to 14 years). J Arthroplast 30:973–979. https://doi.org/10.1016/j.arth.2015.01.003
12. Czekaj J, Fary C, Gaillard T, Lustig S (2017) Does low-constraint mobile bearing knee prosthesis give satisfactory results for severe coronal deformities? A five to twelve year follow up study. Int Orthop 41:1369–1377. https://doi.org/10.1007/s00264-017-3452-z
13. Saragaglia D, Sigwalt L, Gaillot J, Morin V, Rubens-Duval B, Pailhé R (2017) Results with eight and a half years average follow-up on two hundred and eight e-Motion FP® knee prostheses, fitted using computer navigation for knee osteoarthritis in patients with over ten degrees genu varum. Int Orthop. https://doi.org/10.1007/s00264-017-3618-8
14. Argenson JN, Scuderi GR, Komistek RD, Scott WN, Kelly MA, Aubaniac JM (2005) In vivo kinematic evaluation and design considerations related to high flexion in total knee arthroplasty. J Biomech 38:277–284
15. Mazzucchelli L, Deledda D, Rosso F, Ratto N, Bruzzone M, Bonasia DE, Rossi R (2016) Cruciate retaining and cruciate substituting ultra-congruent insert. Ann Transl Med 4:2. https://doi.org/10.3978/j.issn.2305-5839.2015.12.52
16. Thomsen MG, Husted H, Bencke J, Curtis D, Holm G, Troelsen A (2012) Do we need a gender-specific total knee replacement? A randomised controlled trial comparing a high-flex and a gender-specific posterior design. J Bone Joint Surg Br 94:787–792. https://doi.org/10.1302/0301-620X.94B6.28781
17. Laskin RS (1991) Total knee replacement. Springer-Verlag, London, p 268
18. Bargren JH, Blaha JD, Freeman MAR (1983) Alignment in total knee arthroplasty: correlated biomechanical and clinical observations. Clin Orthop 173:178–183
19. Ecker ML, Lotke PA, Windor RE, Cello JP (1987) Long term results after total condylar knee arthroplasty. Clin Orthop 216: 151–158
20. Hood RW, Vanni M, Insall JN (1981) The correction of knee alignment in 225 consecutive total condylar knee replacements. Clin Orthop 160:94–105
21. Hsu H, Garg A, Walker PS, Spector M, Ewald FC (1989) Effect of knee component alignment on tibial load distribution with clinical correlation. Clin Orthop 248:135–144
22. Jeffrey RS, Morris RW, Benham RA (1991) Coronal alignment after total knee replacement. J Bone Joint Surg Br 73:709–714

23. Lotke PA, Ecker ML (1977) Influence of positioning of prosthesis in total knee replacement. J Bone Joint Surg Am 59:77–79
24. Ranawat CS, Boachie-Adjei O (1988) Survivorship analysis and results of total condylar knee arthroplasty. Clin Orthop 226:6–13
25. Ritter MA, Faris PM, Keating E, Meding JB (1994) Postoperative alignment of total knee replacement: its effects on survival. Clin Orthop 299:153–157
26. Tew M, Waugh W (1985) Tibial-femoral alignment and the results of knee replacement. J Bone Joint Surg Br 67:551–556
27. Picard F, Leitner F, Saragaglia D, Cinquin P (1997) Mise en place d'une prothèse totale du genou assistée par ordinateur: A propos de 7 implantations sur cadavre. Rev Chir Orthop Reparatrice Appar Mot 83(Suppl. II):31
28. Leitner F, Picard F, Minfelde R, Schultz HJ, Cinquin P, Saragaglia D (1997) Computer-assisted knee surgical total replacement. In: lecture note in computer science: CURMed-MRCAS'97. Springer Verlag, Berlin-Heidelberg, pp 629–638
29. Saragaglia D, Picard F, Chaussard C, Montbarbon E, Leitner F, Cinquin P (2001) Mise en place des prothèses totale du genou assistée par ordinateur: comparaison avec la technique conventionnelle. A propos d'une étude prospective randomisée de 50 cas. Rev Chir Orthop Reparatrice Appar Mot 87:18–28
30. Saragaglia D, Roberts J (2005) Navigated osteotomies around the knee in 170 patients with osteoarthritis secondary to genu varum. Orthopaedics 28(Suppl n° 10):S1269–S1274
31. Saragaglia D, Mercier N, Colle PE (2010) Computer-assisted osteotomies for genu varum deformity: which osteotomy for which varus? Int Orthop 34:185–190
32. Saragaglia D, Blaysat M, Mercier N, Grimaldi M (2012) Results of forty-two computer-assisted double level osteotomies for severe genu varum deformity. Int Orthop 36:999–1003. https://doi.org/10.1007/s00264-011-1363-y
33. Saragaglia D, Picard F, Refaie R (2012) Navigation of the tibial plateau alone appears to be sufficient in computer-assisted unicompartmental knee arthroplasty. Int Orthop 36:2479–2483. https://doi.org/10.1007/s00264-012-1679-2
34. Saragaglia D, Marques Da Silva B, Dijoux P, Cognault J, Gaillot J, Pailhé R (2017) Computerised navigation of unicondylar knee prostheses: from primary implantation to revision to total knee arthroplasty. Int Orthop 41:293–299. https://doi.org/10.1007/s00264-016-3293-1
35. Nizard RS, Porcher R, Ravaud P, Vangaver E, Hannouche D, Bizot P et al (2004) Use of the Cusum technique for evaluation of a CT-based navigation system for total knee replacement. Clin Orthop Relat Res 425:180–188
36. Weise M, Schmidt K, Willburger RE (2004) Clinical experience with CT-based VectorVision system. In: Stiehl JB, Konermann WH, Haaker RG (eds) Navigation and robotics in total joint and spine surgery. Springer-Verlag, Berlin, pp 301–303
37. Sparmann M, Wolke B (2004) Knee endoprosthesis navigation with the Stryker system. In: Stiehl JB, Konermann WH, Haaker RG (eds) Navigation and robotics in total joint and spine surgery. Springer-Verlag, Berlin, pp 319–323
38. Perlick L, Bäthis H, Lüring C, Tingart M, Grifka J (2004) CT-based and CT-free navigation with the BrainLAB VectorVision system in total knee arthroplasty. In: Stiehl JB, Konermann WH, Haaker RG (eds) Navigation and robotics in total joint and spine surgery. Springer-Verlag, Berlin, pp 304–310
39. Stindel E, Briard JL, Merloz P, Plaweski S, Dubrana F, Lefevre C et al (2002) Bone morphing: 3D morphological data for total knee arthroplasty. Comp Aid Surg 7:156–168
40. Hagena FW, Kettrukat M, Christ RM, Hackbart M (2004) Fluoroscopy-based navigation in genesis II total knee arthroplasty with Medtronic « Viking » system. In: Stiehl JB, Konermann WH, Haaker RG (eds) Navigation and robotics in total joint and spine surgery. Springer-Verlag, Berlin, pp 330–335
41. Victor J, Hoste D (2004) Image-based computer-assisted total knee arthroplasty leads to lower variability in coronal alignment. Clin Orthop Relat Res 428:131–139
42. Mason JB, Fehring TK, Estok R, Banel D, Fahrbach K (2007) Meta-analysis of alignment outcomes in computer-assisted total knee arthroplasty surgery. J Arthroplast 22(8):1097–1106
43. Brin YS, Nikolaou VS, Joseph L, Zukor DJ, Antoniou J (2011) Imageless computer assisted versus conventional total knee replacement. A Bayesian meta-analysis of 23 comparative studies. Int Orthop 35(3):331–339
44. Cheng T, Zhao S, Peng X, Zhang X (2012) Does computer-assisted surgery improve postoperative leg alignment and implant positioning following total knee arthroplasty? A meta-analysis of randomized controlled trials. Knee Surg Sports Traumatol Arthrosc 20(7):1307–1322
45. Hetaimish BM, Khan MM, Simunovic N, Al-Harbi HH, Bhandari M, Zalzal PK (2012) Meta-analysis of navigation vs conventional total knee arthroplasty. J Arthroplast 27(6):1177–1182
46. Lee DH, Park JH, Song DI, Padhy D, Jeong WK, Han SB (2010) Accuracy of soft tissue balancing in TKA: comparison between navigation-assisted gap balancing and conventional measured resection. Knee Surg Sports Traumatol Arthrosc 18(3):381–387
47. Kim YH, Kim JS, Choi Y, Kwon OR (2009) Computer-assisted surgical navigation does not improve the alignment and orientation of the components in total knee arthroplasty. J Bone Joint Surg Am 91(1):14–19
48. Burnett RSJ, Barrack RL (2013) Computer-assisted total knee arthroplasty is currently of no proven clinical benefit: a systematic review. Clin Orthop Relat Res 471(1):264–276
49. Rebal BA, Babatunde OM, Lee JH, Geller JA, Patrick DA, Macaulay W (2014) Imageless computer navigation in total knee arthroplasty provides superior short term functional outcomes: a meta-analysis. J Arthroplast 29(5):938–944
50. De Steiger RN, Liu YL, Graves SE (2015) Computer navigation for total knee arthroplasty reduces revision rate for patients less than sixty-five years of age. J Bone Joint Surg Am 97(8):635–642
51. Baumbach JA, Willburger R, Haaker R, Dittrich M, Kohler S (2016) 10 year survival of navigated versus conventional TKAs: a retrospective study. Orthopedics 39(3 Suppl):S72–S76. https://doi.org/10.3928/01477447-20160509-21
52. Schnurr C, Güdden I, Eysel P, König DP (2012) Influence of computer navigation on TKA revision rates. Int Orthop 36(11):2255–2260. https://doi.org/10.1007/s00264-012-1606-6
53. Saragaglia D, Picard F (2004) Computer-assisted implantation of total knee endoprosthesis with no pre-operative imaging: the kinematic model. In: Stiehl JB, Konermann WH, Haaker RG (eds) Navigation and robotics in total joint and spine surgery. Springer-Verlag, Berlin, pp 226–233
54. Thiengwittayaporn S, Fusakul Y, Kangkano N, Jarupongprapa C, Charoenphandhu N (2016) Hand-held navigation may improve accuracy in minimally invasive total knee arthroplasty: a prospective randomized controlled trial. Int Orthop 40(1):51–57. https://doi.org/10.1007/s00264-015-2848-x
55. Goh GS, Liow MH, Lim WS, Tay DK, Yeo SJ, Tan MH (2016) Accelerometer-based navigation is as accurate as optical computer navigation in restoring the joint line and mechanical axis after total knee arthroplasty: a prospective matched study. J Arthroplast 31(1):92–97. https://doi.org/10.1016/j.arth.2015.06.048
56. Iorio R, Mazza D, Drogo P, Bolle G, Conteduca F, Redler A, Valeo L, Conteduca J, Ferretti A (2015) Clinical and radiographic outcomes of an accelerometer-based system for the tibial resection in total knee arthroplasty. Int Orthop 39(3):461–466. https://doi.org/10.1007/s00264-014-2541-5
57. Koenen P, Schneider MM, Fröhlich M, Driessen A, Bouillon B, Bäthis H (2016) Reliable alignment in total knee arthroplasty by

the use of an iPod-based navigation system. Adv Orthop 2016: 2606453. https://doi.org/10.1155/2016/2606453

58. Maderbacher G, Schaumburger J, Keshmiri A, Barthel M, Springorum HR, Craiovan B, Grifka J, Baier C (2015) Pinless navigation in total knee arthroplasty: navigation reduced by the maximum? Int Orthop 39(3):455–460. https://doi.org/10.1007/s00264-014-2529-1
59. Howell SM, Papadopoulos S, Kuznik K, Ghaly LR, Hull ML (2015) Does varus alignment adversely affect implant survival and function six years after kinematically aligned total knee arthroplasty? Int Orthop 39(11):2117–2124. https://doi.org/10.1007/s00264-015-2743-5
60. Kalairajah Y, Cossey AJ, Verrall GM, Ludbrook G, Spriggins AJ (2006) Are systemic emboli reduced in computer-assisted knee surgery? A prospective, randomised, clinical trial. J Bone Joint Surg Br 88(2):198–202
61. McConnell J, Dillon J, Kinninmonth A, Sarungi M, Picard F (2012) Blood loss following total knee replacement is reduced when using computer-assisted versus standard methods. Acta Orthop Belg 78(1):75–78
62. Jenny J-Y, Picard F (2017) Learning navigation—learning with navigation. A review. SICOT J 3:39. https://doi.org/10.1051/sicotj/2017025
63. Saragaglia D, Chaussard C, Rubens-Duval B (2006) Navigation as a predictor of soft tissue release during 90 cases of computer-assisted total knee arthroplasty. Orthopedics 29(10 Suppl):S137–S138
64. Mullaji A, Shetty GM (2009) Computer-assisted total knee arthroplasty for arthritis with extra-articular deformity. J Arthroplast 24(8):1164–1169
65. Kim KK, Heo YM, Won YY, Lee WS (2011) Navigation-assisted total knee arthroplasty for the knee retaining femoral intramedullary nail, and distal femoral plate and screws. Clin Orthop Surg 3(1):77–80. https://doi.org/10.4055/cios.2011.3.1.77
66. Tigani D, Masetti G, Sabbioni G, Ben Ayad R, Filanti M, Fosco M (2012) Computer-assisted surgery as indication of choice: total knee arthroplasty in case of retained hardware or extra-articular deformity. Int Orthop 36(7):1379–1385. https://doi.org/10.1007/s00264-011-1476-3