Review

Computer-assisted surgery in total knee replacement: advantages, surgical procedure and review of the literature

N. Confalonieri, A. Biazzo
Orthopaedic Traumatologic Institute Pini/CTO, Milano, Italy

Summary. *Introduction:* Total knee replacement (TKR) is one of the most frequent orthopaedic procedures performed every year. At the same time 20% of patients who underwent TKR are not satisfied with the outcome. The reasons are unknown; we think that a mechanical alignment beyond 3° of varus-valgus can represent the most important cause of failure of TKR and consequently patient dissatisfaction. *Materials and Methods:* Neutral mechanical alignment is the main goal in every TKR: this can be achieved through different tools, such as extramedullary and intramedullary guides, patient-specific instrumentation (PSI) and computer-assisted surgery (CAS). The aim of this review is to compare the different alignment techniques in TKR, to describe CAS procedure and CAS results in recent literature. *Results:* Regarding the intramedullary guide, there is an increased risk of fatty embolism; there are great limitations on its use, or even impossibility, in cases of bone deformity and sequelae of trauma. Regarding the extramedullary guide, it becomes more difficult to use in cases of great obesity or increased soft-tissue volume around the tibia. PSI for TKR has been introduced to improve alignment, reduce outliers, operation time and the risk of fatty embolism by avoidance of intramedullary canal violation. Recent randomized controlled trials and meta-analysis proved no advantage of PSI in improving mechanical axis and implant survivorship. *Discussion:* CAS has provided to be a useful tool in assisting the surgeon to achieve more accurate post-operative mechanical axis through precise and reproducible bone cuts and ligament balancing. Two meta-analyses definitively proved that CAS technique improves mechanical axis and implant survivorship and one recent meta-analysis demonstrated that CAS provides better mechanical alignment and higher functional scores at short-term follow-up. (www.actabiomedica.it)

Key words: computer, TKR, knee, prosthesis, robot, knee replacement, technology

Introduction

Total knee replacement (TKR) is one of the most frequent orthopaedic procedures performed every year. The number of TKRs carried out in the United States is estimated to increase by 673% before 2030 (1). At the same time 20% of patients who underwent TKR are not satisfied with the outcome (2, 3). The reasons are unknown but we think that a mechanical alignment beyond 3° of varus-valgus can represent the most important cause of mechanical failure of a TKR and consequently patient dissatisfaction.

Restoring the mechanical axis in TKR is a key factor to optimize the load sharing and prevent the eccentric loading through the prosthesis, which could avoid implant loosening, instability or early failure (4, 5). The concept of mechanical axis was introduced by Insall et al. (6) in 1985: it requires that both femoral and tibial cuts must be perpendicular to the mechanical axis of the femur and tibia. The purpose is to create equal load distribution on the new joint line.

Although Parratte et al. (7) found that a post-operative mechanical axis of 0° did not improve the rate of survival 15 years post-operatively, several authors suggested that restoration of a neutral mechanical axis improves durability following TKR (8-10).

Nowadays, neutral mechanical alignment is considered the "gold standard" and the primary aim in every TKR. This can be achieved through different surgical techniques, such as extramedullary and intramedullary guides, patient-specific instrumentation (PSI) and computer-assisted surgery (CAS), each one with advantages and disadvantages. Regarding the intramedullary guide, there is an increased risk of fatty embolism (11), there are great limitations on its use, or even impossibility, in cases of bone deformity, sequelae of trauma or presence of osteosynthesis material that obliterates the medullary canal. Regarding the extramedullary guide, it becomes more difficult to use in cases of great obesity or increased soft-tissue volume around the tibia. PSI for TKR has been introduced to improve alignment, reduce outliers, operation time and the risk of fatty embolism by avoidance of intramedullary canal violation. Recent randomized controlled trails and meta-analysis proved no advantage of PSI in improving mechanical axis and implant survivorship (12, 13).

In the late 1990s, two teams, one led by Picard and Leitner in France (14), the other led by Krackow in Buffalo, New York (15), concurrently developed the technology for modern imageless computer-assisted TKR. Approved by the FDA in 2001, these systems utilize infrared communication to track the spatial positioning of patient anatomy and surgical equipment. The system's subsequent calculations allow the surgeon to evaluate bony cuts prior to their execution and also allow the surgeon to check these cuts after they are performed.

Different recent meta-analyses (references) has provided CAS to be a useful tool in assisting the surgeon to achieve more accurate post-operative mechanical axis through precise and reproducible bone resection and ligament balancing (16). CAS for TKR has been reported to provide more precise component placement in coronal, sagittal and rotational alignment; more accurate bone cuts and better restoration of coronal limb alignment (17-19). In a meta-analysis of 29 studies comparing CAS with conventional technique, Mason et al. (20) demonstrated 90.4% of patients with a femoral varus/valgus alignment within 2° of the femoral mechanical axis (versus 65.9% in the conventional group) and 95.2% of patients with a tibial varus/valgus alignment within 2° of the tibial mechanical axis (versus 79.7% of the conventional group).

Operative technique

Since 1998, in our department, different systems based on computer-assisted navigation systems without use of computed tomography (CT) have been used in >1.000 joint replacements (knee and hip), and according to these navigation systems, all data have been acquired in the operating theater during the procedures.

Step 1. Prepare the surgical field according to your preferences. However, the patient should be in supine position just with the feet outside allowing the knee to be easily flexed at 90°. Place a support by the side of the thigh to maintain lower limb position even with the knee flexed. The surgeon is supposed to be in front of the patient and able to check the mechanical axis constantly.

Step 2. We always position a metal locator in the center of the hip as further limb alignment reference during the surgery in order to keep a constant check on axial adjustment and on the correct positioning of the prosthetic femoral component (a x-ray of the hip should give you the position of the metal locator).

Step 3. With the patient under anesthesia, the surgeon should evaluate clinically the limb deformity and how much can be reduced manually acting on the knee.

Step 4. The skin incision with the limb flexed at 90° should not exceed 12–14 cm in a median or paramedian medial direction. Then the surgeon should perform knee arthrotomy and should evaluate all compartments and confirm or not surgical indication.

Step 5. Insert the screws for the infrared reflecting diodes (LED) of the computer scanner with tiny skin incision of <1 cm. One diode should be located on the femur and one on the tibia both 10 cm away from the joint line. Proceed with the lower limb data acquisition using the computer. Just moving the limb and using mathematical models, the navigator determines the axis, which goes through the rotation center of the femoral head, the center of the knee and ankle. Acquire the deepest point in the more damaged tibial plateau with a mobile pointer, the center of the tibial plateau, both posterior femoral condyles, the superior femoral cortex, and medial and lateral epicondyles, always according to the indications on the screen step by step.

Step 6. With the data reported on the screen, the surgeon can recalculate with numbers the deformity and how much can be corrected. Data processing empowers the system to produce onscreen information related to the mechanical function in frontal and lateral projection within the entire given range of movement (Figure 1). It suggests implant size, amount of bone according to the deformity and tridimensional implant alignment.

Step 7. The deformity should always be reducible manually; otherwise, the surgeon should proceed with a slight release of the ligaments under the direct control of the system.

Step 8. Position the tibial cut guide and connect with a mobile diode to the computer. The height of the resection is based on the concept of “minimum bone cut”: this is a simple rule we have been experimented since 2001. The amount of bone to be resected is given by the difference between prosthesis thickness and arthritic knee deformity. For example, if a patient had a valgus deformity of 8° and assuming a total thickness prosthesis of 19 mm, the planned minimum bone to be resected is 11 mm (19-8=11. Figure 2).

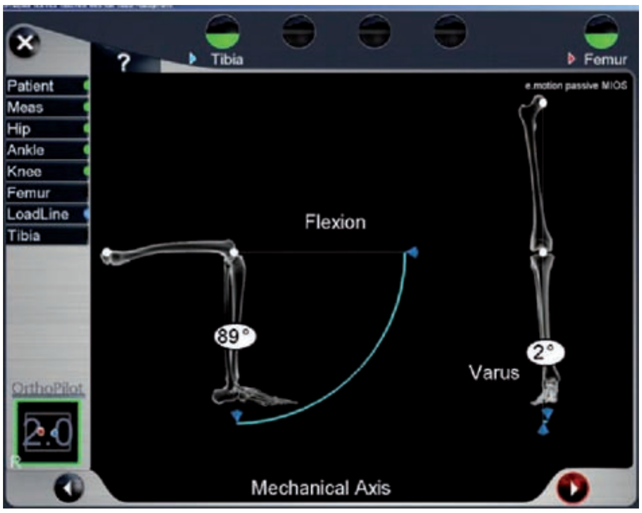

Figure 1. Flexion and extension mechanical axis

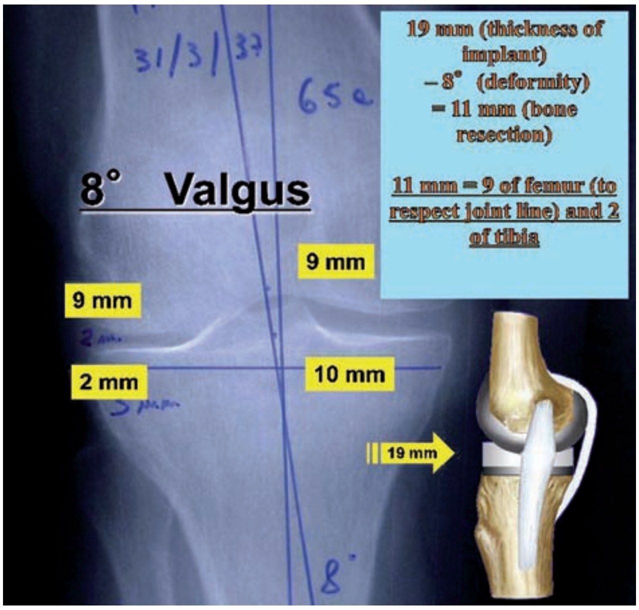

Figure 2. Eight degrees valgus knee. The minimum bone cut: the entity of bone resection is given by the difference between prosthesis thickness and axial deviation angle. We have to cut 9 mm of femur because it drives the joint line

Then you should plan tibial cut orientation (varus–valgus) and checked it on the display (Figure 3). The slope will be according to the implant slope. After fixing the guide, use a blade for the horizontal cut.

Step 9. The femoral cuts have been already planned according joint space in flexion and extension,

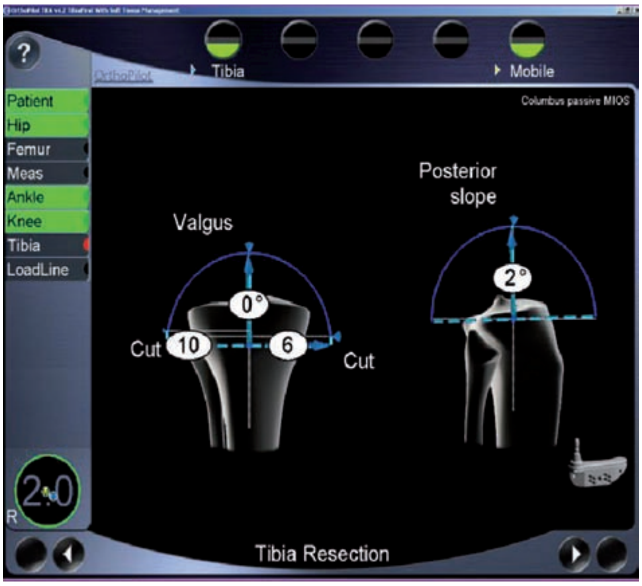

Figure 3. Navigated tibial cut

both in the medial and lateral compartment, using spreaders (Figure 4).

If gap balancing is not correct, you have to plan femoral cuts, rotation of the femoral component, size of prosthesis and polyethylene thickness in order to equalize the gaps (Table 1). In difficult cases with deformities >10 degrees, you have to perform ligament release to equalize the gaps. In impossible cases, you have to use hinge prosthesis.

Step 10. Then you perform distal femoral cut and check it on the screen. Position the chamfers of the corresponding size, with adequate femoral rotation, planned and checked on the screen. Perform the remaining cuts (Figure 5).

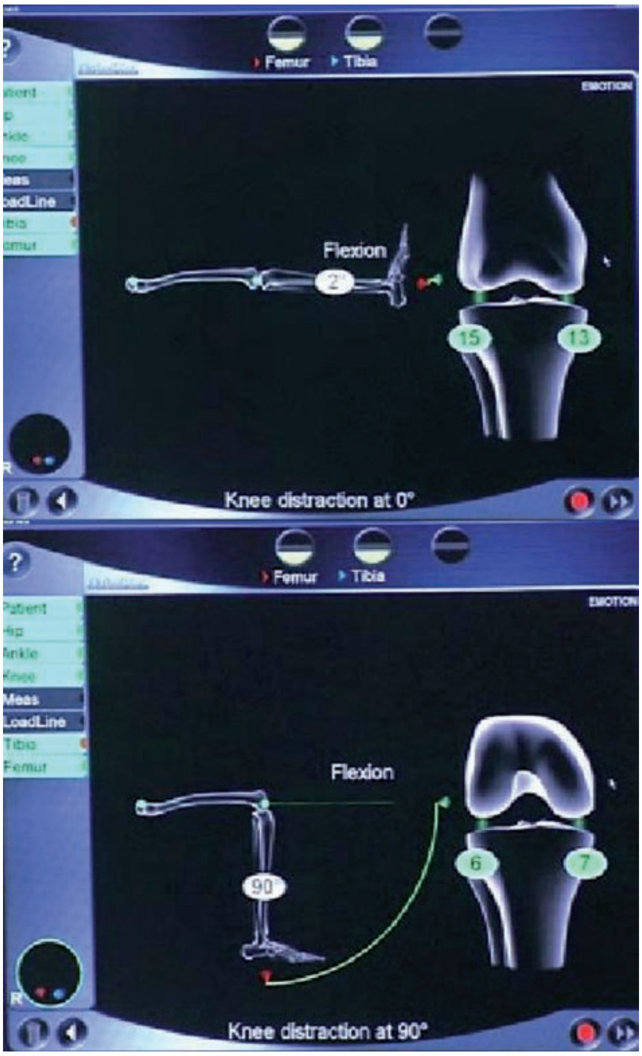

Figure 4. Gap balancing in extension (0 degrees) and flexion (90 degrees)

Step 11. Position the tibial and femoral trial components with polyethylene thickness, check the mechanical axis and the ligament balance in full range of motion, always reading the values and the morphology of the inferior limb in motion on the computer screen.

Step 12. We first implant the tibial component and then the femoral one; the limb should be extended and compressed securely against the chest of the operator to complete the operation. Final recording of data is performed for the personal computerized patient file charts.

Step 13. Wound suture and post-operative x-ray. This is the only check for those who do not use CAS.

Discussion

Several studies have reported significant difference in implant survivorship when a traditional safe zone of 0-3 degrees was used to define aligned versus malaligned knees respect to a neutral mechanical axis. For example, Berend et al. (8) reported a statistically increased rate of failure of tibial components positioned in >3.9° of varus. Ritter et al. (9) found an increased rate of failure in knees with a femoral component in >8° of anatomical valgus and in those with a varus tibial component relative to the tibial axis. Collier et al. (10) reported a significantly greater loss of thickness of polyethylene in the medial compartment when the limb was aligned in >5° of varus.

On the other hand, some authors have found no statistically significant differences in survivorship between aligned versus malaligned knees respect to a neutral mechanical axis. One of the most influential studies is reported by Parratte et al. (7), who retrospectively reviewed the clinical and radiological data of 398 TKRs. They found that a post-operative mechanical axis of 0° did not improve the rate of survival 15 years post-operatively and stated that the description of alignment as a dichotomous variable (aligned versus malaligned) provided little value in regards to durability. Neverthless, they concluded that "until additional data can be generated to more accurately determine the ideal post-operative limb alignment in individual patients, a neutral mechanical axis remains a reasonable target and should be considered as the standard for

Table 1. Gap balancing algorithm in TKR

TKR	Extension space balanced	Extension space is thight	Laxity in extension space
Flexion space balanced	PERFECT	**Release posterior capsule** **Increase distal femoral cut with the same polyethylene thickness** **Removal of osteophytes and posterior condyles**	**Distal femoral wedges** **Increase tibial slope with higher polyethylene thickness** **Decrease femoral size component with higher polyethylene thickness**
Flexion space is thight	**Undersize femoral component with the same poly** **Release PCL in CR implant** **Increase tibial slope with the same poly thickness**	**Increase tibial cut with the same polyethylene thickness**	**Decrease femoral size with higher polyethylene thickness** **Distal femoral wedges and increase distal cut and/or tibial slope**
Laxity in flexion space	**Increase tibial cut and decrease tibial slope with higher polyethylene** **Increase femoral size with the same polyethylene thickness** **Increase distal femoral cut with bigger polyethylene**	**Increase distal femoral cut with bigger polyethylene thickness** **Increase femoral size component and/or augmentation with posterior femoral wedges with the same polyethylene thickness**	**Bigger polyethylene thickness**

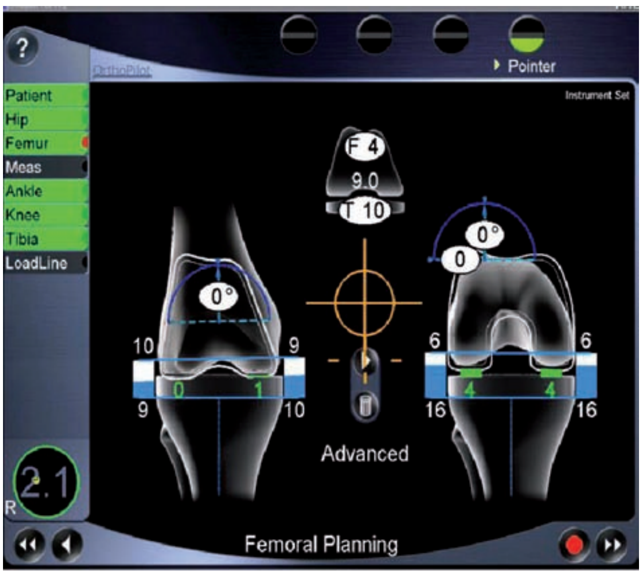

Figure 5. Navigated femoral planning

comparison if other alignment targets are introduced". Similar to Parratte et al. (7), also other authors found that the relationship between coronal alignment and survivorship was weak (21-23).

The precision with which the implants are placed directly affects patient outcome as implant position and alignment influence the stability, durability and patellar tracking. Evaluating the alignment in total knee arthroplasty and functional outcome with respect to the alignment is the need of the hour.

Orthopaedic surgeons have different tools to achieve these targets, such as conventional techniques (intramedullary or extramedullary guides), PSI and CAS. Although intra- and extramedullary alignment are used worldwide, several errors have been reported, due to variations in bony anatomy, visual misjudgement by the surgeon or limitations of the technique.

Several studies reported that with conventional technique the percentage of malaligned knees is between 20% and 30% (24-28). It has been shown that only 70-80% cases would obtain the ideal positioning of the prosthesis when using the intramedullary system (29). Recently, navigation systems have been developed to improve the accuracy of align- ment of the components in TKR. So far, only a few studies have been published, reporting the results of computer-assisted TKR.

Computer navigation has the potential to play a role in improving mechanical alignment and outcomes in TKR. In our Department we started using CAS in 1999, both in unicompartmental knee replacement (UKR) and TKR, then in association with patellofemoral replacement, bi-UKR and tri-UKR. CAS is also a teaching tool in TKR, especially in inexpert hands. In 2010 we published a paper in which we demonstrated that surgeons with different experience in CAS and knee surgery could perform TKRs with similar mechanical alignment (179.2° vs 178.1° with no statistical significant difference), proving CAS as teaching tool to train inexpert surgeons in knee replacement surgery (30). Then, in 2012 we demonstrated that a beginner can reproduce the results of an expert TKR surgeon by means of navigation after a learning curve of 16 cases; this represents the break-even point after which no statistically significant difference is observed between the expert surgeon and the beginner utilizing CAS (31). In 2012 we checked usefulness of CAS in post-traumatic knee arthritis comparing a group of CAS TKR performed in traumatic knee arthritis with CAS TKR in atraumatic knee arthritis. We found no statistical significant difference between the two group in terms of functional outcomes (32).

CAS in TKR provides more accurate bone cuts, more precise component placement in the coronal, sagittal and rotational planes, better restoration of coronal limb alignment and lower gap asymmetry (33-37).

Two recent meta-analyses definitively proved that CAS technique provided better mechanical axis and implant survivorship (38-39), but only Rebal et al. definitively demonstrated that CAS improves clinical outcomes at short-term follow-up (40). This meta-analysis collected only randomized controlled studies with two groups, CAS versus conventional technique in TKR: twenty-one papers were analysed, with the hypothesis that imageless computer navigation improves TKR short-term functional outcomes scores by producing superior post-operative alignment. They concluded that TKR performed with computer navigation was more likely to be within 3° of ideal mechanical alignment (87.1% vs 73.7%, P<0.01) and had a higher increase in Knee Society Score at 3-month follow-up (68.5% vs 58.1%, P=0.03) and at 12-32 month follow-up (53.1% vs 45.8%, P<0.01). The mean operative time for CAS TKR was 101.6 minutes vs 83.3 for conventional TKR (P< 0.01) (40).

These results demonstrate that CAS is a useful and teaching tool in TKR, even in inexpert hands; it allows reproducible results, providing better mechanical alignment and superior functional outcomes in the short-term follow-up. This increase requires the investment of additional and financial resources (40).

Additional operating time is needed when using navigation systems in TKR. However, after an initial learning curve, the computer-assisted surgical procedure took only 10-15 minutes longer to perform. This additional time is acceptable in clinical practice. In future, it may be reduced by an improvement of the computer-assisted workflow and by the development of specific navigation-adapted instruments.

References

1. 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-A: 780-5.
2. 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: 57-63.
3. Dossett HG, Swartz GJ, Estrada NA, LeFevre GW, Kwasman BG. Kinematically versus mechanically aligned total knee arthroplasty. Orthopedics 2012; 35: e160-9.
4. Blakeney WG, Khan RJ, Wall SJ. Computer-assisted techniques versus conventional guides for component alignment in total knee arthroplasty: a randomized controlled trial. J Bone Joint Surg Am 2011; 93: 1377-84.
5. Tingart M, Lüring C, Bäthis H, Beckmann J, Grifka J, Perlick L. Computer-assisted total knee arthroplasty versus the conventional technique: how precise is navigation in clinical routine? Knee Surg Sports Traumatol Arthrosc 2008; 16: 44-50.

6. Insall JN, Binazzi R, Soudry M, Mestriner LA. Total knee arthroplasty. Clin Orthop Relat Res 1985; 192: 13-22.
7. Parratte S, Pagnano MW, Trousdale RT, Berry DJ. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. J Bone Joint Surg Am 2010; 15(92): 2143-9.
8. Berend ME, Ritter MA, Meding JB, Faris PM, Keating EM, Redelman R, et al. Tibial component failure mechanisms in total knee arthroplasty. Clin Orthop Relat Res 2004; 428: 26-34.
9. Ritter MA, Davis KE, Meding JB, Pierson JL, Berend ME, Malinzak RA. The effect of alignment and BMI on failure of total knee replacement. J Bone Joint Surg Am 2011; 7(93): 1588-96.
10. Collier MB, Engh CA Jr, McAuley JP, Engh GA. Factors associated with the loss of thickness of polyethylene tibial bearings after knee arthroplasty. J Bone Joint Surg Am 2007; 89: 1306-14.
11. Fahmy NR, Chandler HP, Danylchuk K, Matta EB, Sunder N, Siliski JM. Blood-gas and circulatory changes during total knee replacement. Role of the intramedullary alignment rod. J Bone Joint Surg Am 1990; 72: 19-26.
12. Huijbregts HJ, Khan RJ, Sorensen E, Fick DP, Haebich S. Patient-specific instrumentation does not improve radiographic alignment or clinical outcomes after total knee arthroplasty. Acta Orthop 2016; 1: 1-9.
13. Nunley RM, Ellison BS, Zhu J, Ruh EL, Howell SM, Barrack RL. Do patient-specific guides improve coronal alignment in total knee arthroplasty? Clin Orthop Relat Res 2012; 470: 895-902.
14. Delph SL, Stulberg SD, Davies B, Picard F, Leitner F. Computer assisted knee replacement. Clin Orthop Relat Res 1998; 354: 49-56.
15. Krackow KA, Bayers-Thering M, Phillips MJ, Bayers-Thering M, Mihalko WM. A new technique for determining proper mechanical axis alignment during total knee arthroplasty: progress toward computer-assisted TKA. Orthopedics 1999; 22(7): 698-702.
16. Pitto RP, Graydon AJ, Bradley L, Malak SF, Walker CG, Anderson IA. Accuracy of a computer-assisted navigation system for total knee replacement. J Bone Joint Surg Br 2004; 88: 601-5.
17. Rosenberger RE, Hoser C, Quirbach S, Attal R, Hennerbichler A, Fink C. Improved accuracy of component alignment with the implementation of image-free navigation in total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 2007; 16: 249-57.
18. Scuderi GR, Fallaha M, Masse V, Lavigne P, Amiot LP, Berthiaume MJ. Total knee arthroplasty with a novel navigation system within the surgical field. Orthop Clin North Am 2014; 45: 167-73.
19. Stöckl B, Nogler M, Rosiek R, Fischer M, Krismer M, Kessler O. Navigation improves accuracy of rotational alignment in total knee arthroplasty. Clin Orthop Relat Res 2004; 426: 180-6.
20. Mason JB, Fehring TK, Estok R, Banel D, Fahrbach K. Meta-analysis of alignment outcomes in computer-assisted total knee arthroplasty surgery. J Arthroplasty 2007; 22: 1097-106.
21. Bonner TJ, Eardley WG, Patterson P, Gregg PJ. The effect of post-operative mechanical axis alignment on the survival of primary total knee replacements after a follow-up of 15 years. J Bone Joint Surg Br 2011; 93: 1217-22.
22. Choong PF, Dowsey MM, Stoney JD. Does accurate anatomical alignment result in better function and quality of life? Comparing conventional and computer-assisted total knee arthroplasty. J Arthroplasty 2009; 24: 560-9.
23. Magnussen RA, Weppe F, Demey G, Servien E, Lustig S. Residual varus alignment does not compromise results of TKAs in patients with preoperative varus. Clin Orthop Relat Res 2011; 469: 3443-50.
24. Bäthis H, Perlick L, Tingart M, Lüring C, Zurakowski D, Grifka J. Alignment in total knee arthroplasty. A comparison of computer-assisted surgery with the conventional technique. J Bone Joint Surg Br 2004; 86: 682-7.
25. Manhunt KS, Gopalakrishna KG, Vineeth G. Evaluation of alignment in total knee arthroplasty: a prospective study. Eur J Orthop Surg Traumatol 2015; 25: 895-903.
26. Matziolis G, Krocker D, Weiss U, Tohtz S, Perka C. A prospective, randomized study of computer-assisted and conventional total knee arthroplasty. Three-dimensional evaluation of implant alignment and rotation. J Bone Joint Surg Am 2007; 89: 236-43.
27. Mielke RK, Clemens U, Jens JH, Kershally S. Navigation in knee endoprosthesis implantation--preliminary experiences and prospective comparative study with conventional implantation technique. Z Orthop Ihre Grenzgeb 2011; 139: 109-16.
28. Petersen TL, Engh GA. Radiographic assessment of knee alignment after total knee arthroplasty. J Arthroplasty 1988; 3: 67-72.
29. Mahaluxmivala J, Bankes MJ, Nicolai P, Aldam CH, Allen PW The effect of surgeon experience on component positioning in 673 Press Fit Condylar posterior cruciate-sacrificing total knee arthroplasties. J Arthroplasty 2011; 16: 635-40.
30. Manzotti A, Cerveri P, De Momi E, Pullen C, Confalonieri N. Relationship between cutting errors and learning curve in computer-assisted total knee replacement. Int Orthop 2010; 34(5): 655-62.
31. Confalonieri N, Chemello C, Cerveri P, Manzotti A. Is computer-assisted total knee replacement for beginners or experts? Prospective study among three groups of patients treated by surgeons with different levels of experience. J Orthop Traumatol 2012; 13(4): 203-10.
32. Manzotti A, Pullen C, Cerveri P, Chemello C, Confalonieri N. Post traumatic knee arthritis: navigated total knee replacement without hardware removal. Knee 2014; 21(1): 290-4.
33. Decking R, Markmann Y, Fuchs J, Puhl W, Scharf HP. Leg axis after computer-navigated total knee arthroplasty: a prospective randomized trial comparing computer-navigated and manual implantation. J Arthroplasty 2005; 20: 282-8.

34. Fehring TK, Mason JB, Moskal J, Pollock DC, Mann J, Williams VJ. When computer-assisted knee replacement is the best alternative. Clin Orthop Relat Res 2006; 452: 132-6.
35. Jenny JY, Clemens U, Kohler S, Kiefer H, Konermann W, Miehlke RK. Consistency of implantation of a total knee arthroplasty with a non-image-based navigation system: a case-control study of 235 cases compared with 235 conventionally implanted prostheses. J Arthroplasty 2005; 20: 832-9.
36. Kim YH, Park JW, Kim JS. Computer-navigated versus conventional total knee arthroplasty a prospective randomized trial. J Bone Joint Surg Am 2012; 94: 2017-24.
37. Weng YJ, Hsu RW, Hsu WH. Comparison of computer-assisted navigation and conventional instrumentation for bilateral total knee arthroplasty. J Arthroplasty 2009; 24: 668-73.
38. Fu Y, Wang M, Liu Y, Fu Q. Alignment outcomes in navigated total knee arthroplasty: a meta-analysis. Knee Surg Sports Traumatol Arthrosc 2012; 20: 1075-82.
39. Hetaimish BM, Khan MM, Simunovic N, Al-Harbi HH, Bhandari M, Zalzal PK. Meta-analysis of navigation vs conventional total knee arthroplasty. J Arthroplasty 2012: 27: 1177-82.
40. Rebal BA, Babatunde OM, Lee JH, Geller JA, Patrick DA Jr, Macaulay W. Imageless computer navigation in total knee arthroplasty provides superior short term functional outcomes: a meta-analysis. J Arthroplasty 2014; 29: 938-44.

Received: ??????
Accepted: ?????
Correspondence:
N. Confalonieri
Orthopaedic Traumatologic Institute Pini/CTO
Via Bignami 1 - Milano, Italy
E-mail: norberto.confalonieri@gmail.con