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Current state of computer navigation and robotics in unicompartmental and total knee arthroplasty: a systematic review with meta-analysis

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Abstract Recently, there is a growing interest in surgical variables that are intraoperatively controlled by orthopaedic surgeons, including lower leg alignment, component positioning and soft tissues balancing. Since more tight control over these factors is associated with improved outcomes of unicompartmental knee arthroplasty and total knee arthroplasty (TKA), several computer navigation and robotic-assisted systems have been developed. Although mechanical axis accuracy and component positioning have been shown to improve with computer navigation, no superiority in functional outcomes has yet been shown. This could be explained by the fact that many differences exist between the number and type of surgical variables these systems control. Most systems control lower leg alignment and component positioning, while some in addition control soft tissue balancing. Finally, robotic-assisted systems have the additional advantage of improving surgical precision. A systematic search in PubMed, Embase and Cochrane Library resulted in 40 comparative studies and three registries on computer navigation reporting outcomes of 474,197 patients, and 21 basic science and clinical studies on robotic-assisted knee arthroplasty. Twenty-eight of these comparative computer navigation studies reported Knee Society Total scores in 3504 patients. Stratifying by type of surgical variables, no significant differences were noted in outcomes between surgery with computer-navigated TKA controlling for alignment and component positioning versus conventional TKA ($p = 0.63$). However, significantly better outcomes were noted following computer-navigated TKA that also controlled for soft tissue balancing versus conventional TKA (mean difference 4.84, 95 % Confidence Interval 1.61, 8.07, $p = 0.003$). A literature review of robotic systems showed that these systems can, similarly to computer navigation, reliably improve lower leg alignment, component positioning and soft tissues balancing. Furthermore, two studies comparing robotic-assisted with computer-navigated surgery reported superiority of robotic-assisted surgery in controlling these factors. Manually controlling all these surgical variables can be difficult for the orthopaedic surgeon. Findings in this study suggest that computer navigation or robotic assistance may help managing these multiple variables and could improve outcomes. Future studies assessing the role of soft tissue balancing in knee arthroplasty and long-term follow-up studies assessing the role of computer-navigated and robotic-assisted knee arthroplasty are needed.

Keywords Computer navigation · Robotics · Unicompartmental knee arthroplasty · Total knee arthroplasty · Soft tissue balancing

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Introduction

Unicompartmental knee arthroplasty (UKA) and total knee arthroplasty (TKA) are two reliable treatment options for knee osteoarthritis. Recent systematic reviews have reported 92 % 10-year survivorship of medial UKA [125] and 95 % of TKA [79], although registries have reported lower rates [2, 3, 19, 85, 87]. Over the last two decades, there is a growing interest towards perioperative variables that are controlled by the orthopaedic surgeon. These variables, which include lower leg alignment, soft tissues balance, joint line maintenance and the alignment, sizing and fixation of the components, have been shown to improve knee arthroplasty outcomes (Table 1).

Most often these variables are manually controlled with the aid of extramedullary or intramedullary alignment guides. Since more tight control over these factors is associated with improved outcomes and prosthesis survival (Table 1), several computer navigation systems have been developed. Usage of these systems for knee arthroplasty has grown over the last 15 years; in Australia, in 2003 2.4 % of all primary TKA was performed with the use of computer navigation, while this increased to 23.8 % in 2013 [2, 31].

It is important to acknowledge differences in computer navigation systems with regard to the number and type of variables they aim to control. Most systems control lower leg alignment and component positioning, while some systems additionally control soft tissue balancing (Table 2). This balancing of soft tissues throughout the range of motion (ROM) is considered important since this may prevent the knee being tight or lax and subsequent abnormal

Table 1 Overview of surgical variables that are important for knee arthroplasty along with the consequences of not correctly controlling these variables according to the literature

Surgical variables	Consequence	References
Lower leg alignment	Aseptic loosening, polyethylene wear, OA progression (UKA)	[50, 96, 98, 102, 123, 126, 128]
Soft tissue balancing	Instability, polyethylene wear, pain	[5, 90, 95, 100, 129]
Joint line maintenance	Aseptic loosening, polyethylene wear, OA progression (UKA)	[51, 54, 88, 144]
Component alignment	Aseptic loosening, pain, instability	[7, 28, 86, 101, 143]
Component size	Mediolateral overhang, pain, instability	[13, 14, 20, 82, 116, 138]
Component fixation	Aseptic loosening, tibial subsidence, periprosthetic fractures	[8, 35, 38, 53, 56, 132]

OA osteoarthritis, *UKA* unicompartmental knee arthroplasty

Table 2 Overview of different systems of studies reporting Knee Society Scores following computer-navigated TKA or UKA

Systems for TKA	Developer	Alignment lower leg/component	Soft tissue balancing	Robotic	References
Ci navigation	DePuy	Yes	No	No	[9, 36, 48, 121, 142]
Electromagnetic	Zimmer	Yes	No	No	[119]
Knee navigation	Stryker	Yes	No	No	[15, 43, 45, 71, 103, 115]
Navitrack navigation	Zimmer	Yes	No	No	[47]
OrthoPilot	Aesculap	Yes	No	No	[32, 44, 57, 78, 118, 134, 135]
PiGalileo	Plus Orthopedics	Yes	Yes	No	[52, 75, 109]
Ci Mi TKR	BrainLab/DePuy	Yes	Yes	No	[12, 92]
Vector vision	BrainLab	Yes	Yes	No	[24, 49, 62–64, 70, 127]
ROBODOC	Aesculap	Yes	Yes	Yes	[65, 93, 113, 114]
Systems for UKA	**Developer**	**Lower leg/component alignment**	**Additional soft tissue balancing**	**Robotic**	**References**
Acrobot	Acrobot Co. Ltd.	Yes	No	No	[27]
Knee navigation	Stryker	Yes	No	No	[59]
OrthoPilot	Aesculap	Yes	No	No	[105, 112, 131]
Vector vision	BrainLab	Yes	Yes	No	[141]
RIO	MAKO	Yes	Yes	Yes	[42]
Monet—UKA	Orthokey	Yes	Yes	Yes	[73]

Studies or registries that had different systems or not reported systems used [2, 41, 99, 104] wear patterns [129], instability [90] and decreased proprioception [5]. A different group of recently developed systems are robotic-assisted systems, which not only control aforementioned surgical variables but also improve the surgical precision [67, 110, 122]. Finally, over recent years patient-specific instrumentations have been developed [84], but this will remain outside the focus of this article since it is discussed in another article in this issue.

Several meta-analyses have assessed whether these systems indeed improve the control of these surgical variables in TKA [10, 17, 22, 29, 39, 46, 74, 81, 106] and UKA [83, 130]. Many studies showed that mechanical axis accuracy is improved using computer navigation and mechanical axis outlier risk is decreased compared to conventional surgery (Table 3). Furthermore, it has been shown that the component positioning is more accurate using computer navigation (Table 3). Although these radiographic factors are indicative for an increased failure risk [7, 18, 28, 50, 58, 86, 96, 98], meta-analyses have not clearly shown differences in outcomes between navigated and conventional TKA (Table 3). Similarly for robotic systems, several cadaveric studies [25, 80, 136] and randomized clinical trials (RCTs) [27, 65, 93, 113, 114] have shown that robotic-assisted systems provide more accuracy and decrease outliers when compared to conventional knee arthroplasty but studies comparing outcomes are scarce [112, 114].

Aim of this review was to discuss current state of computer navigation and robotic-assisted systems in knee arthroplasty. Aforementioned meta-analyses have clearly shown that these systems improve radiographic alignment and component positioning but the role on outcomes and survivorship remains unclear. Therefore, a systematic search of the literature was performed to guide this discussion on the current state of computer navigation and robot systems. Goals of this study were fourfold: (1) to perform a meta-analysis of computer-navigated versus conventional knee arthroplasty outcomes, (2) to conduct a systematic review of literature on robotic-assisted knee arthroplasty, (3) to discuss studies comparing computer-navigated to robotic-assisted knee arthroplasty and (4) discuss the current state of computer-assisted and robotic-assisted knee arthroplasty in the light of these findings.

Review

Search strategy and study design

A systematic search was performed using PRISMA guidelines [77]. Databases of PubMed, Embase and Cochrane were searched for studies on computer-navigated or robotic-assisted knee arthroplasty on 15 January 2016. Search criterion was the pattern "*(robot* OR navigat* OR comput*) AND knee arthroplasty*" for English studies since 2000. It was filtered for clinical studies, clinical trials, comparative studies, controlled clinical trials, observational studies and randomized clinical trials. After removing duplicates, two authors (*** and ***) independently scanned all studies for eligibility by title and abstract. These selected studies were then scanned by full text on inclusion and exclusion criteria. Finally, national registries and article reference lists were scanned for additional data, and contact persons of robotic-assisted systems were contacted to request a list of their publications. Consensus was reached for all articles.

Inclusion criteria for the meta-analysis consisted of English-language studies that (1) reported revision rates or functional outcomes of TKA or UKA, (2) were comparative studies, (3) were minimum level III studies [133] published between 2000 and 2016. Exclusion criteria consisted of studies that (1) did not report revisions or mean follow-up or (2) did not report mean score, standard deviation or number of patients (required for meta-analysis).

The level of evidence for all studies was determined by using the adjusted Oxford Centre for Evidence-Based Medicine [133], and methodological quality of the included studies was graded according to the Grades of Recommendation, Assessment, Development, and Evaluation (GRADE) [4]. Two authors (*** and ***) assessed all studies with any disagreement mediated by a third author (***). Consensus was reached for all studies.

All data were collected in a datasheet in Excel 2011 (Microsoft Corp., Redmond, WA, USA) and included study authors, publication year, mean follow-up, number of procedures and failures and reported functional outcomes. Revision rates were reported as annual revision rate (ARR), which is defined as the number of revisions divided by the total observed component years and enables comparison of revision rates between groups with different follow-up time [61, 89, 108, 125]. TKA functional outcomes were stratified by studies using computer navigation for lower leg and component alignment with or without correcting for soft tissue balancing (both with virtual software or tensor devices [63]). Since Knee Society Score (KSS) was most commonly used in TKA, studies reporting KSS Total were included for meta-analysis. When necessary, KSS Total scores were calculated by summing the KSS Knee and KSS Function scores, while the standard deviation was calculated by the square root of the pooled variance [124]. Outcomes were stratified by follow-up time and were reported as odds ratios (OR) or mean difference (MD) with 95 % confidence.

Statistical analysis was performed using Microsoft Excel and Review Manager 5.3 (Nordic Cochrane Center, Copenhagen, Denmark). Using forest plots, dichotomous outcomes were used to compare ARR, while continuous

Table 3 Overview of recent meta-analyses that compared radiographic and functional outcomes of computer navigation versus conventional knee arthroplasty

Authors	Ref	Year	Journal	TKA/UKA	Mech./outl.	Femoral component				Tibial component				Functional outcomes
						Coronal angle	Sagittal angle	Rotation	Slope	Coronal angle	Sagittal angle	Rotation	Slope	
Alcelik et al.	[1]	2016	J Arthroplasty	TKA	Nav.	None	–	–	–	Nav.	–	–	–	No dif. (6 months)
Bauwens et al.	[10]	2007	JBJS Am	TKA	Nav.	–	–	–	–	–	–	–	–	–
Brin et al.	[17]	2011	Int Orth	TKA	Nav.	Nav.	–	–	–	Nav.	–	–	–	–
Cheng et al.	[22]	2011	J Surg Res	TKA	Nav.	Nav.	Nav.	No Dif.	–	Nav.	Nav.	No Dif.	Nav.	–
Cheng et al.	[21]	2012	The Knee	TKA	–	–	–	–	–	–	–	–	–	No dif. (6 months)
Cheng et al.	[23]	2012	KSSTA	TKA	Nav.	Nav.	Nav.	–	–	Nav.	Nav.	–	Nav.	–
Fu et al.	[39]	2012	KSSTA	TKA	Nav.	Nav.	–	–	–	Nav.	–	–	–	–
Hetaimish et al.	[46]	2012	J Arthroplasty	TKA	Nav.	Nav.	Nav.	–	–	Nav.	Nav.	–	–	–
Mason et al.	[74]	2007	J Arthroplasty	TKA	Nav.	Nav.	Nav.	–	Nav.	Nav.	Nav.	–	Nav.	–
Meijer et al.	[76]	2014	CORR	TKA	Nav.	–	–	No Dif.	–	–	–	No Dif.	–	–
Moskal et al.	[81]	2014	J Knee Surg	TKA	Nav.	Nav.	–	No Dif.	Nav.	Nav.	–	–	Nav.	No dif. ("insufficient data")
Rebal et al.	[97]	2014	J Arthroplasty	TKA	Nav.	–	–	–	–	–	–	–	–	Nav. (12 months)
Thienpont et al.	[120]	2013	The Knee	TKA	Nav.	Nav.	Nav.	–	–	Nav.	Nav.	–	–	–
Zamora et al.	[139]	2014	ANZ J Surg	TKA	Nav.	–	–	–	–	–	–	–	–	No dif. (no pooled analysis)
Weber et al.	[130]	2012	KSSTA	UKA	Nav.	Nav.	Nav.	–	–	Nav.	Nav.	–	–	–

Ref indicates reference; TKA, total knee arthroplasty; UKA, unicompartmental knee arthroplasty; outl., outliers > 2° or > 3°; Mech., mechanical axis; outl., outliers; Nav., computer navigation; No Pref.; no significant difference between both

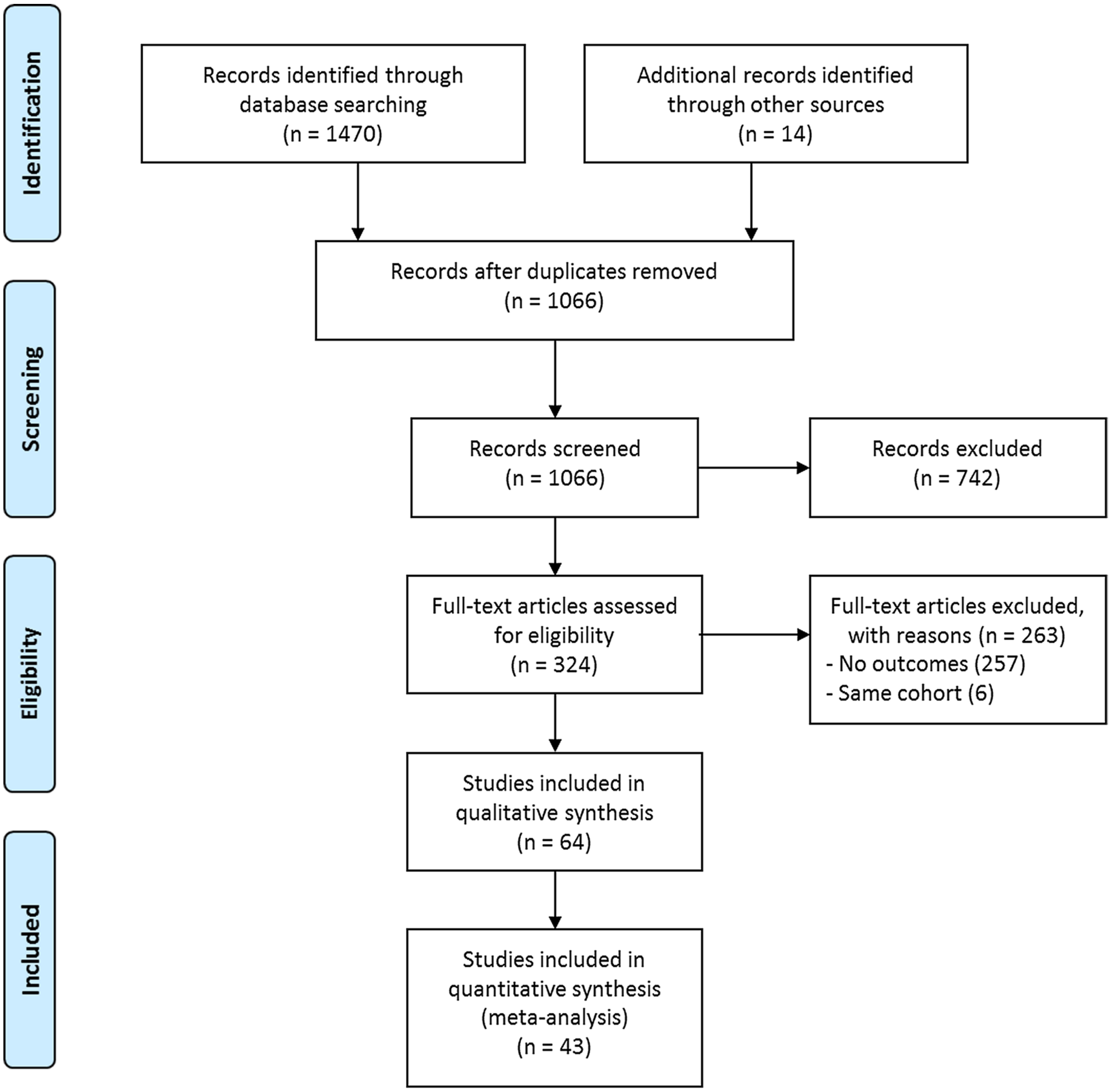

Fig. 1 PRISMA flow chart of study

outcomes were used to compare functional outcomes. Heterogeneity was expressed via I^2 statistic and Chi-square tests. Random-effects models were used for all analyses [16]. A funnel plot was used to assess publication bias in any of the included studies. Outcomes were considered significant when $p < 0.05$.

After removing duplicates, reviewing title, abstract and full text of the articles, a total of 40 studies [9, 12, 15, 24, 32, 36, 42–45, 47–49, 52, 57, 59, 62–64, 70, 71, 73, 75, 78, 92, 103–105, 109, 112, 115, 118, 119, 121, 127, 131, 134, 135, 141, 142] and three registries [2, 41, 99] were included (Fig. 1) that included a total of 474,197 patients. Sixteen of the included studies were level I studies [9, 24, 32, 43, 48, 57, 64, 71, 75, 92, 103, 109, 115, 119, 127, 135], while nine studies were level II [15, 44, 45, 62, 63, 105, 134, 141, 142] and 15 were level III therapeutic studies [12, 36, 42, 47, 49, 52, 59, 70, 73, 78, 104, 112, 118, 121, 131]. Quality of evidence and recommendation using the GRADE criteria varied between low and high with most of the studies having high quality [4]. No publication bias could be detected in any of the analyses using funnel plots.

Outcomes of computer-navigated versus conventional knee arthroplasty

Six studies [42, 59, 73, 112, 131, 140] reported UKA revisions in a total of 200 patients with 6 failures following navigated and 4 failures following conventional UKA. Only two studies reported a follow-up of more than 2 years (both nine years follow-up) [59, 112] and both showed no

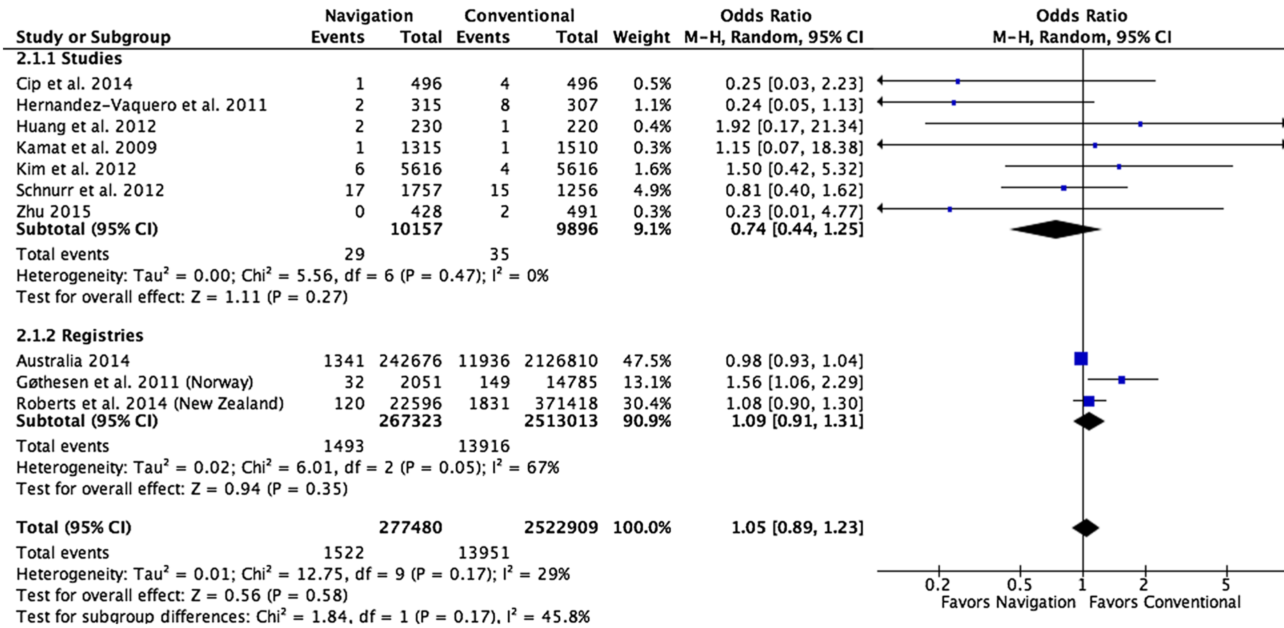

Fig. 2 Forest plots are shown of cohort studies (*upper*) and registries (*lower*) reporting TKA annual revision rates in patients undergoing navigated versus conventional TKA surgery

differences in survivorship. The ARR in computer-assisted UKA surgery (1.01) was not significantly different compared to conventional surgery (0.64, $p = 0.49$).

Six studies [59, 73, 105, 112, 131, 141] reported functional outcomes of computer-navigated versus conventional UKA in a total of 262 patients. Four studies [73, 105, 131, 141] reported follow-up of two year or less and did not find any differences between both procedures. Two studies reported outcomes at nine-year follow-up [59, 112]. Konyves et al. did not find any significant differences which were attributed to the small sample size [59], while Song et al. showed significant better outcomes and pain scores in navigated compared to conventional UKA [112]. Forest plot analysis was not performed due to different outcome scoring systems.

Seven studies [24, 45, 48, 52, 57, 104, 142] and three registries [2, 41, 99] reported ARR of computer navigation versus conventional TKA surgery in 470,231 patients. Analysis showed an ARR of 0.55 in patients who underwent computer-navigated TKA surgery and an ARR of 0.56 in patients who underwent conventional TKA surgery ($p = 0.58$, Fig. 2).

Twenty-eight studies [9, 12, 15, 24, 32, 36, 43, 44, 47, 49, 57, 62–64, 70, 71, 75, 78, 92, 103, 109, 115, 118, 119, 121, 127, 134, 135] reported KSS Total scores in 3504 patients who underwent TKA surgery. Patients reported better outcomes following computer-navigated TKA compared to conventional TKA [MD 2.86 (0.96, 4.76), $p = 0.003$]. This was both seen at short-term follow-up of 6 months and 1 year [MD 5.20 (3.41, 7.00) and MD 8.46 (0.65, 16.28), respectively] and mid-term follow-up (≥4 years) [MD (2.65 0.96, 4.76)] (Fig. 3).

Seventeen studies [9, 15, 32, 36, 43, 44, 47, 57, 71, 78, 103, 115, 118, 119, 121, 134, 135] reported the use of navigation systems for lower leg alignment and component positioning without differences in KSS Total scores ($p = 0.63$, Fig. 4). Analysis of 11 studies [12, 24, 49, 62–64, 70, 75, 92, 109, 127] also controlling soft tissue balance using navigation showed that patients undergoing computer-navigated TKA reported better functional outcomes than conventional TKA [MD 4.84 (1.61, 8.07), $p = 0.003$] (Fig. 5).

Studies reporting outcomes of robotic-assisted surgery

Robotic-assisted surgery is a relatively new concept, so fewer clinical comparative studies have been published. Twenty-one studies [11, 25–27, 30, 34, 55, 60, 65, 66, 68, 69, 72, 80, 93–95, 107, 111, 113, 114] were identified that assessed the role of robotic-assisted surgery on the aforementioned surgical variables (Table 1).

For UKA, Pearle et al. [94] showed in the first ten patients treated with the MAKO system (MAKO Surgical Corp., Fort Lauderdale, FL, USA) that all patients were within 1.6° of the mechanical axis. Dunbar et al. [34] showed in a series of 20 patients reliable positioning of both components using this system. Lonner et al. and Smith et al. also reported reliable component positioning using the Navio System (Blue Belt Technologies Inc., Plymouth, MN, USA) [69, 111]. Furthermore, Plate et al. [95] showed

Study or Subgroup	Navigation Mean	Navigation SD	Navigation Total	Conventional Mean	Conventional SD	Conventional Total	Weight	Mean Difference IV, Random, 95% CI
2.2.1 6 months								
Hasegawa et al. 2011	171	17.5	50	170	16.6	50	3.4%	1.00 [−5.69, 7.69]
Lee et al. 2015	149	20.1	30	146.9	27.1	60	2.2%	2.10 [−7.84, 12.04]
Matziolis et al. 2007	149	34	32	144	29	28	1.1%	5.00 [−10.94, 20.94]
Pang et al. 2011	148	5.4	70	141.9	6.5	70	5.5%	6.10 [4.12, 8.08]
Spencer et al. 2007	149.1	24.5	30	151.8	29.8	30	1.4%	−2.70 [−16.50, 11.10]
Stulberg et al. 2006	147.4	26.8	38	146.6	24.1	40	1.9%	0.80 [−10.53, 12.13]
Yaffe et al. 2013	147.4	26.8	29	146.6	24.2	34	1.6%	0.80 [−11.90, 13.50]
Subtotal (95% CI)			**279**			**312**	**17.2%**	**5.20 [3.41, 7.00]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 4.98$, df = 6 (P = 0.55); $I^2 = 0\%$								
Test for overall effect: Z = 5.68 (P < 0.00001)								
2.2.2 1 year								
Barrett et al. 2011	181.4	18.1	81	179.2	17.3	85	4.0%	2.20 [−3.19, 7.59]
Decking et al. 2007	176.2	17.2	27	168.4	24.9	25	1.8%	7.80 [−3.92, 19.52]
Lehnen et al. 2011	177	21	43	159	30	121	2.8%	18.00 [9.76, 26.24]
Spencer et al. 2007	153.5	26.9	30	152.2	36	30	1.1%	1.30 [−14.78, 17.38]
Van Strien et al. 2009	145	24.4	17	131	36.2	21	0.8%	14.00 [−5.35, 33.35]
Subtotal (95% CI)			**198**			**282**	**10.5%**	**8.46 [0.65, 16.28]**
Heterogeneity: $Tau^2 = 45.39$; $Chi^2 = 10.89$, df = 4 (P = 0.03); $I^2 = 63\%$								
Test for overall effect: Z = 2.12 (P = 0.03)								
2.2.3 2 years								
Bin Abd Razak et al. 2014	162	12.7	234	158	14.7	234	5.3%	4.00 [1.51, 6.49]
Bonutti et al. 2008	181	14	50	186	12.7	50	4.1%	−5.00 [−10.24, 0.24]
Ek et al. 2008	164	67	50	106	43	50	0.7%	58.00 [35.93, 80.07]
Hoppe et al. 2007	169	19.4	20	170	24.6	20	1.4%	−1.00 [−14.73, 12.73]
Kim et al. 2012	179	5.8	73	178	6.4	38	5.4%	1.00 [−1.43, 3.43]
Lee et al. 2015	157.7	20.1	30	160.2	23.9	60	2.4%	−2.50 [−11.90, 6.90]
Lehnen et al. 2011	177	21	43	159	30	121	2.8%	18.00 [9.76, 26.24]
Lin et al. 2013	187.6	6.2	30	190.1	5.9	35	5.1%	−2.50 [−5.46, 0.46]
Lutzner et al. 2013	157.4	21.9	34	151.1	26	33	1.9%	6.30 [−5.23, 17.83]
Pang et al. 2011	161.8	12.2	70	153.2	11.4	70	4.7%	8.60 [4.69, 12.51]
Schmitt et al. 2007	179.6	21.9	30	187.7	15.7	30	2.3%	−8.10 [−17.74, 1.54]
Singh et al. 2012	181.5	16.6	70	184.5	22.9	26	2.3%	−3.00 [−12.62, 6.62]
Spencer et al. 2007	156.4	33.1	30	158.9	29	30	1.2%	−2.50 [−18.25, 13.25]
Yang et al. 2010	153	15.5	23	162.9	14.3	24	2.7%	−9.90 [−18.44, −1.36]
Subtotal (95% CI)			**787**			**821**	**42.2%**	**1.97 [−1.91, 5.84]**
Heterogeneity: $Tau^2 = 36.02$; $Chi^2 = 83.38$, df = 13 (P < 0.00001); $I^2 = 84\%$								
Test for overall effect: Z = 1.00 (P = 0.32)								
2.2.4 ≥4 years								
Cip et al. 2014	192.3	9.9	71	182.5	20.2	72	4.1%	9.80 [4.60, 15.00]
Harvie et al. 2012	157	29.8	24	148.1	38	22	0.8%	8.90 [−10.96, 28.76]
Hoppe et al. 2007	178	15.2	24	178	20	28	2.3%	0.00 [−9.58, 9.58]
Huang et al. 2014	193	3.5	34	189.8	6	36	5.4%	3.20 [0.91, 5.49]
Luring et al. 2012	168.2	21.9	50	166.2	21.4	50	2.7%	2.00 [−6.49, 10.49]
Lutzner et al. 2013	150.2	30.4	34	149	28	33	1.4%	1.20 [−12.79, 15.19]
Molfetta et al. 2008	174	7.6	30	172	7.7	30	4.7%	2.00 [−1.87, 5.87]
Thiengwittayaporn et al. 2013	152.3	5.5	63	151.2	4.5	61	5.6%	1.10 [−0.67, 2.87]
Tolk et al. 2012	156.4	29.8	50	155.6	28.8	50	1.9%	0.80 [−10.69, 12.29]
Yaffe et al. 2013	167.9	35.3	29	172.8	27.7	34	1.1%	−4.90 [−20.77, 10.97]
Subtotal (95% CI)			**409**			**416**	**30.0%**	**2.65 [0.84, 4.46]**
Heterogeneity: $Tau^2 = 1.72$; $Chi^2 = 11.90$, df = 9 (P = 0.22); $I^2 = 24\%$								
Test for overall effect: Z = 2.87 (P = 0.004)								
Total (95% CI)			**1673**			**1831**	**100.0%**	**2.86 [0.96, 4.76]**
Heterogeneity: $Tau^2 = 15.94$; $Chi^2 = 126.09$, df = 35 (P < 0.00001); $I^2 = 72\%$								
Test for overall effect: Z = 2.96 (P = 0.003)								
Test for subgroup differences: $Chi^2 = 6.12$, df = 3 (P = 0.11), $I^2 = 50.9\%$								

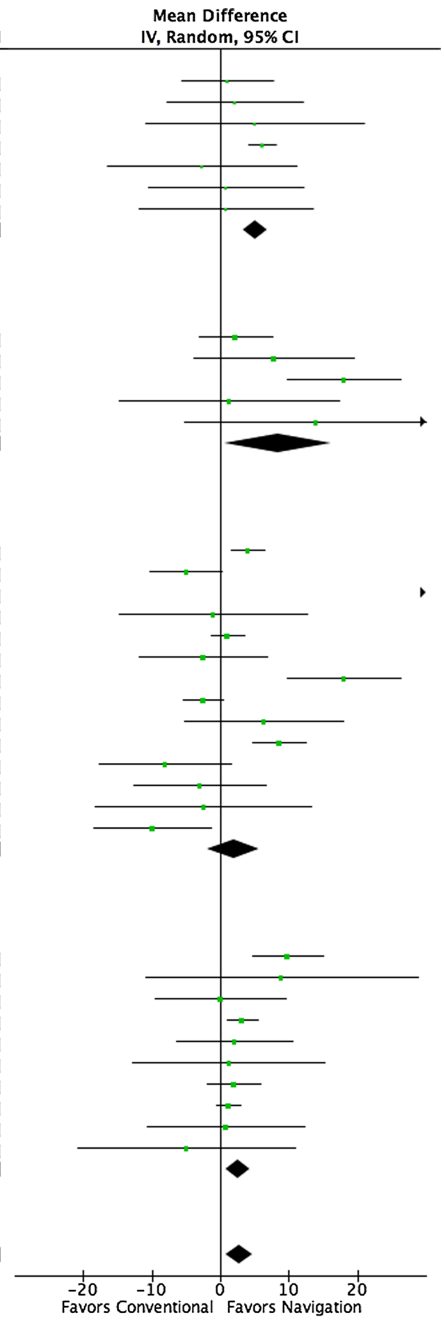

Fig. 3 Forest plots are shown of cohort studies reporting TKA functional outcomes in patients undergoing navigated versus conventional TKA surgery

in 52 patients undergoing UKA using the MAKO system that soft tissue balancing was accurate up to 0.53 mm compared to the operative plan and 83 % of the cases were within 1 mm throughout ROM.

The control of these surgical variables was also assessed in studies comparing robotic-assisted to manual UKA. Cobb et al. [27] and Lonner et al. [68] showed in clinical studies using the Acrobot (Acrobot Co. Ltd, London, UK) and MAKO system, respectively, that robotic-assisted surgery had increased mechanical axis accuracy compared to manual UKA. Citak et al. [25] found in a cadaveric study more accurate implant positioning of both components using the MAKO system, while Lonner et al. also found more accurate tibial component alignment in a clinical study using the MAKO system [68]. Furthermore, MacCallum et al. showed in a clinical study that robotic-assisted

Study or Subgroup	Navigation Mean	SD	Total	Conventional Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
Barrett et al. 2011	181.4	18.1	81	179.2	17.3	85	9.0%	2.20 [-3.19, 7.59]
Bonutti et al. 2008	181	14	50	186	12.7	50	9.2%	-5.00 [-10.24, 0.24]
Decking et al. 2007	176.2	17.2	27	168.4	24.9	25	3.9%	7.80 [-3.92, 19.52]
Ek et al. 2008	164	67	50	106	43	50	1.4%	58.00 [35.93, 80.07]
Harvie et al. 2012	157	29.8	24	148.1	38	22	1.7%	8.90 [-10.96, 28.76]
Hasegawa et al. 2011	171	17.5	50	170	16.6	50	7.6%	1.00 [-5.69, 7.69]
Hoppe et al. 2007	169	19.4	20	170	24.6	20	3.1%	-1.00 [-14.73, 12.73]
Kim et al. 2012	179	5.8	73	178	6.4	38	12.5%	1.00 [-1.43, 3.43]
Lutzner et al. 2013	157.4	21.9	34	151.1	26	33	4.0%	6.30 [-5.23, 17.83]
Molfetta et al. 2008	174	7.6	30	172	7.7	30	10.8%	2.00 [-1.87, 5.87]
Schmitt et al. 2007	179.6	21.9	30	187.7	15.7	30	5.1%	-8.10 [-17.74, 1.54]
Spencer et al. 2007	156.4	33.1	30	158.9	29	30	2.5%	-2.50 [-18.25, 13.25]
Stulberg et al. 2006	147.4	26.8	38	146.6	24.1	40	4.1%	0.80 [-10.53, 12.13]
Thiengwittayaporn et al. 2013	152.3	5.5	63	151.2	4.5	61	13.1%	1.10 [-0.67, 2.87]
Tolk et al. 2012	156.4	29.8	50	155.6	28.8	50	4.0%	0.80 [-10.69, 12.29]
Yaffe et al. 2013	167.9	35.3	29	172.8	27.7	34	2.4%	-4.90 [-20.77, 10.97]
Yang et al. 2010	153	15.5	23	162.9	14.3	24	5.9%	-9.90 [-18.44, -1.36]
Total (95% CI)			**702**			**672**	**100.0%**	**0.66 [-2.06, 3.38]**

Heterogeneity: $Tau^2 = 13.88$; $Chi^2 = 44.21$, df = 16 (P = 0.0002); $I^2 = 64\%$
Test for overall effect: Z = 0.47 (P = 0.63)

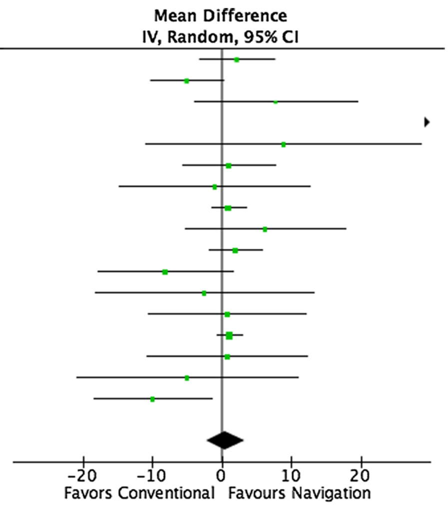

Fig. 4 Forest plots are shown of cohort studies reporting TKA functional outcomes in patients undergoing navigated versus conventional TKA surgery with navigation systems aiming to control for alignment and component position

Study or Subgroup	Navigation Mean	SD	Total	Conventional Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
Bin Abd Razak et al. 2014	162	12.7	234	158	14.7	234	14.3%	4.00 [1.51, 6.49]
Cip et al. 2014	192.3	9.9	71	182.5	20.2	72	11.1%	9.80 [4.60, 15.00]
Huang et al. 2014	193	3.5	34	189.8	6	36	14.5%	3.20 [0.91, 5.49]
Lee et al. 2015	149	20.1	30	146.9	27.1	60	6.3%	2.10 [-7.84, 12.04]
Lehnen et al. 2011	177	21	43	159	30	121	7.7%	18.00 [9.76, 26.24]
Lin et al. 2013	187.6	6.2	30	190.1	5.9	35	13.8%	-2.50 [-5.46, 0.46]
Luring et al. 2012	168.2	21.9	50	166.2	21.4	50	7.5%	2.00 [-6.49, 10.49]
Matziolis et al. 2007	149	34	32	144	29	28	3.3%	5.00 [-10.94, 20.94]
Pang et al. 2011	161.8	12.2	70	153.2	11.4	70	12.7%	8.60 [4.69, 12.51]
Singh et al. 2012	181.5	16.6	70	184.5	22.9	26	6.5%	-3.00 [-12.62, 6.62]
Van Strien et al. 2009	145	24.4	17	131	36.2	21	2.4%	14.00 [-5.35, 33.35]
Total (95% CI)			**681**			**753**	**100.0%**	**4.84 [1.61, 8.07]**

Heterogeneity: $Tau^2 = 17.47$; $Chi^2 = 43.19$, df = 10 (P < 0.00001); $I^2 = 77\%$
Test for overall effect: Z = 2.93 (P = 0.003)

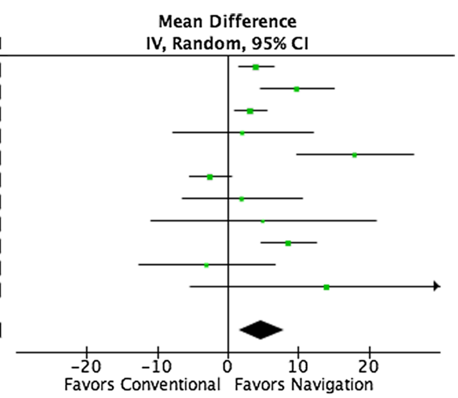

Fig. 5 Forest plots are shown of cohort studies reporting TKA functional outcomes in patients undergoing navigated versus conventional TKA surgery with navigation systems aiming to control for alignment and component position with in addition controlling for soft tissue balance

surgery with the MAKO system was more precise in the coronal and tibial plane in baseplate positioning compared to manual UKA [72]. Coon et al. presented the first short-term outcomes of robotic-assisted surgery in a multicentre study reporting 98.9 % survivorship and 92 % satisfaction rate in 854 patients [30]. The 98.9 % survivorship is higher than other large manual UKA studies at this short-term follow-up, [91, 137] which may indicate that indeed controlling these variables could improve UKA survivorship. However, comparative studies with longer follow-up are clearly needed to draw strong conclusions on this topic.

For TKA, several studies have also assessed the role of robotic surgery on the aforementioned surgical variables. Bellemans et al. [11] showed in a clinical study of 25 cases undergoing TKA using the CASPAR system (URS Ortho, Rastatt, Germany) that no patients had mechanical alignment, tibial or femoral component positioning and rotation beyond 1° of neutral alignment. Siebert et al. also found less mechanical axis outliers using this system compared to conventional TKA [107]. Liow et al. [65] found in all 27 patients mechanical alignment <3° and accurate implant sizing following TKA surgery using the ROBODOC system (Curexo Tech. Corp., Fremont, CA, USA), while Kim et al. [55] reported higher implant accuracy and fewer outliers using the ROBODOC system compared to conventional surgery. Moon et al. [80] and Park et al. [93] found superiority in femoral component positioning using ROBODOC. Song et al. performed two randomized clinical trials comparing ROBODOC robotic-assisted and conventional TKA [113, 114]. They found more reliable mechanical axis alignment and femoral and tibial component positioning using robotic-assisted TKA and also found that 12 patients had a preference for the robotic-assisted TKA leg, while only six chose the conventional leg [113]. In their second study, they assessed soft tissue balancing and found that more robotic-assisted TKA patients had <2 mm flexion–extension gap and more satisfactory posterior cruciate ligament tension compared to conventional TKA [114].

Computer-navigated versus robotic-assisted knee arthroplasty

To the best of our knowledge, only two studies have compared outcomes of robotic-assisted versus computer-navigated TKA surgery [26, 60]. In a retrospective study, Clark and Schmidt compared 52 patients undergoing robotic-assisted TKA using the Praxim system (OMNIlife science, East Taunton, MA, USA) to 29 patients undergoing computer-navigated TKA using eNact Precision Knee Navigation System (Stryker Kalamazoo, MI, USA), which also controls soft tissue balancing [26]. They found that robotic-assisted surgery had shorter surgery time, mechanical alignment 0.5° closer to the neutral mechanical axis and shorter hospital stay when compared to computer navigation. In a cadaver study, Koulalis et al. [60] used the Praxim Total Knee Navigation system (Praxim, Grenoble, France) in both the computer-navigated and robotic-assisted TKA group and added the iBlock (Praxim, Grenoble, France), a motorized cutting-guide positioner, to the robotic-assisted group. They reported less time for femoral cutting, and less resection deviations in coronal and sagittal plane were noted in the robotic-assisted group compared to the computer navigation group.

Current state of computer navigation and robotic-assisted knee arthroplasty

Several meta-analyses have shown that computer navigation improves mechanical alignment, decreases outlier risk and improves component positioning [10, 17, 22, 29, 39, 46, 74, 81, 83, 106, 130] (Table 2). Since many studies suggested a correlation between tighter control of these variables and better outcomes [7, 18, 28, 50, 58, 86, 96, 98], one can expect better outcomes following joint replacement using computer navigation, especially at longer follow-up. However, meta-analyses have failed to show this correlation, which could be explained by the small number of patients, short follow-up and no differentiation between different navigation systems used (Table 3).

In this current study, cohort studies did not reveal differences in ARR between computer navigation and conventional surgery. This was not surprising given the low number of revisions in TKA (64) and UKA (10) and relatively short follow-up (<5 years). Similarly, registries did not show any differences between computer navigation and conventional TKA with mean follow-up also less than 5 years. This is likely due to the relatively new concept of computer navigation, and studies with longer follow-up are necessary to draw strong conclusions on the hypothesis that computer navigation improves implant survivorship.

Although not enough studies were available to draw conclusion on UKA outcomes, several studies reported outcomes following navigated versus conventional TKA. Interestingly, it was noted that significant differences between computer-navigated and conventional surgery were seen when outcomes were stratified by the number and type of variables the systems aimed to control (Figs. 4, 5). These results may indicate that soft tissue balancing plays an important role during TKA. Indeed, many studies have reported that instability is a very common early failure mode in TKA [33, 37, 40], which is often attributed to poor soft tissue balancing [40, 90]. Other studies also showed an increased risk of polyethylene wear, aseptic loosening and pain following poor soft tissue balancing [5, 6, 95, 100, 129]. For example, Pang et al. [92] compared knee laxity in patients operated using computer-navigated TKA, with control for soft tissue balance, versus conventional TKA and found increased laxity in patients undergoing conventional TKA. Soft tissue balancing is a complex procedure and is influenced by several surgical variables including lower leg alignment, the joint line, component rotation and positioning and size of the components [6]. The orthopaedic surgeon now manually controls all these factors, including soft tissue balancing, while these variables influence each other and are different at different flexion angles. Intuitively, it makes sense that computer-assisted surgery could help the orthopaedic surgeon given the complexity of controlling these multiple variables, especially soft tissue balancing, and given the high reliability of soft tissue balancing with computer navigation [117]. Findings in this study suggest that soft tissue balancing could play an important role in knee arthroplasty and that navigation systems controlling soft tissue balancing could improve TKA outcomes. These findings have not been reported previously, and therefore studies are needed to confirm the role of computer navigation and soft tissue balancing in knee arthroplasty.

A review of published studies on robotic-assisted systems shows that many of the aforementioned surgical variables, including alignment, implant positioning and soft tissue balancing, can be reliably controlled by robotic systems and that this is more accurate than manual surgery. The first study reporting robotic-assisted survivorship indeed suggests that survivorship is higher following robotic-assisted UKA compared to other large manual UKA cohorts but comparative studies and RCTs are clearly needed to further assess these outcomes. Furthermore, it is interesting to note that two studies comparing robotic-assisted versus computer navigation TKA [26, 60] reported superiority of robotic-assisted surgery in controlling surgical variables and surgery time. This indicates that for knee arthroplasty both balancing soft tissues and surgical precision are important characteristics of robotic-assisted surgery. Future studies are, however, needed to confirm these findings.

Conclusions

Several studies and meta-analyses have shown that the computer navigation and robotic-assisted surgery improves mechanical axis accuracy and implant positioning. Findings of this meta-analysis suggest that controlling multiple surgical variables, and especially balancing the soft tissues, may play an important role in knee arthroplasty. It is further suggested that robotic-assisted surgery might be superior over computer navigation surgery although more studies are needed on this topic. Furthermore, studies assessing the role of soft tissue balancing in knee arthroplasty and assessing long-term outcomes of computer navigation and robotic-assisted knee arthroplasty are necessary.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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Ethical approval Ethical approval was not obtained because this study was a literature review.

Informed consent Informed consent was not obtained because this study was a literature review.

References

1. Alcelik IA, Blomfield MI, Diana G, Gibbon AJ, Carrington N, Burr S (2016) A comparison of short-term outcomes of minimally invasive computer-assisted vs minimally invasive conventional instrumentation for primary total knee arthroplasty: a systematic review and meta-analysis. J Arthroplasty 31(2):410–418
2. Annual Report 2014 Australian Hip and Knee Arthroplasty Register (2014). https://aoanjrr.dmac.adelaide.edu.au/documents/10180/172286/AnnualReport2014. Accessed 20 Aug 2016
3. Annual Report 2015 Swedish Knee Arthroplasty Register (2015). http://www.myknee.se/pdf/SVK_2015_Eng_1.0.pdf. Accessed 20 Aug 2016
4. Atkins D, Best D, Briss PA, Eccles M, Falck-Ytter Y, Flottorp S, Guyatt GH, Harbour RT, Haugh MC, Henry D, Hill S, Jaeschke R, Leng G, Liberati A, Magrini N, Mason J, Middleton P, Mrukowicz J, O'Connell D, Oxman AD, Phillips B, Schunemann HJ, Edejer T, Varonen H, Vist GE, Williams JW Jr, Zaza S (2004) Grading quality of evidence and strength of recommendations. BMJ 328(7454):1490
5. Attfield SF, Wilton TJ, Pratt DJ, Sambatakakis A (1996) Soft-tissue balance and recovery of proprioception after total knee replacement. J Bone Joint Surg Br 78(4):540–545
6. Babazadeh S, Stoney JD, Lim K, Choong PF (2009) The relevance of ligament balancing in total knee arthroplasty: how important is it? A systematic review of the literature. Orthop Rev (Pavia) 1(2):e26
7. Barbadoro P, Ensini A, Leardini A, d'Amato M, Feliciangeli A, Timoncini A, Amadei F, Belvedere C, Giannini S (2014) Tibial component alignment and risk of loosening in unicompartmental knee arthroplasty: a radiographic and radiostereometric study. Knee Surg Sports Traumatol Arthrosc 22(12):3157–3162
8. Barink M, Verdonschot N, de Waal Malefijt M (2003) A different fixation of the femoral component in total knee arthroplasty may lead to preservation of femoral bone stock. Proc Inst Mech Eng H 217(5):325–332
9. Barrett WP, Mason JB, Moskal JT, Dalury DF, Oliashirazi A, Fisher DA (2011) Comparison of radiographic alignment of imageless computer-assisted surgery vs conventional instrumentation in primary total knee arthroplasty. J Arthroplasty 26(8):1273–1284
10. Bauwens K, Matthes G, Wich M, Gebhard F, Hanson B, Ekkernkamp A, Stengel D (2007) Navigated total knee replacement: a meta-analysis. J Bone Joint Surg Am 89(2):261–269
11. Bellemans J, Vandenneucker H, Vanlauwe J (2007) Robot-assisted total knee arthroplasty. Clin Orthop Relat Res 464:111–116
12. Bin Abd Razak HR, Yeo Jin S, Chong Chi H (2014) Computer navigation results in less severe flexion contracture following total knee arthroplasty. J Arthroplasty 29(12):2369–2372
13. Bonnin MP, Saffarini M, Shepherd D, Bossard N, Dantony E (2015) Oversizing the tibial component in TKAs: incidence, consequences and risk factors. Knee Surg Sports Traumatol Arthrosc 24(8):2532–2540
14. Bonnin MP, Schmidt A, Basiglini L, Bossard N, Dantony E (2013) Mediolateral oversizing influences pain, function, and flexion after TKA. Knee Surg Sports Traumatol Arthrosc 21(10):2314–2324
15. Bonutti PM, Dethmers D, Ulrich SD, Seyler TM, Mont MA (2008) Computer navigation-assisted versus minimally invasive TKA: benefits and drawbacks. Clin Orthop Relat Res 466(11):2756–2762
16. Borenstein M, Hedges LV, Higgins J, Rothstein HR (2009) Introduction to meta-analysis. Wiley, Chichester
17. 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
18. Burnett RS, Nair R, Hall CA, Jacks DA, Pugh L, McAllister MM (2014) Results of the Oxford Phase 3 mobile bearing medial unicompartmental knee arthroplasty from an independent center: 467 knees at a mean 6-year follow-up: analysis of predictors of failure. J Arthroplasty 29(9 Suppl):193–200
19. Centre of excellence of joint replacements (2010) The Norwegian arthroplasty register
20. Chau R, Gulati A, Pandit H, Beard DJ, Price AJ, Dodd CA, Gill HS, Murray DW (2009) Tibial component overhang following unicompartmental knee replacement–does it matter? Knee 16(5):310–313
21. Cheng T, Pan XY, Mao X, Zhang GY, Zhang XL (2012) Little clinical advantage of computer-assisted navigation over conventional instrumentation in primary total knee arthroplasty at early follow-up. Knee 19(4):237–245
22. Cheng T, Zhang G, Zhang X (2011) Imageless navigation system does not improve component rotational alignment in total knee arthroplasty. J Orthop Surg Res 171(2):590–600

23. 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
24. Cip J, Widemschek M, Luegmair M, Sheinkop MB, Benesch T, Martin A (2014) Conventional versus computer-assisted technique for total knee arthroplasty: a minimum of 5-year follow-up of 200 patients in a prospective randomized comparative trial. J Arthroplasty 29(9):1795–1802
25. Citak M, Suero EM, Citak M, Dunbar NJ, Branch SH, Conditt MA, Banks SA, Pearle AD (2013) Unicompartmental knee arthroplasty: is robotic technology more accurate than conventional technique? Knee 20(4):268–271
26. Clark TC, Schmidt FH (2013) Robot-assisted navigation versus computer-assisted navigation in primary total knee arthroplasty: efficiency and accuracy. ISRN Orthop 2013:794827
27. Cobb J, Henckel J, Gomes P, Harris S, Jakopec M, Rodriguez F, Barrett A, Davies B (2006) Hands-on robotic unicompartmental knee replacement: a prospective, randomised controlled study of the acrobot system. J Bone Joint Surg Br 88(2):188–197
28. Collier MB, Eickmann TH, Sukezaki F, McAuley JP, Engh GA (2006) Patient, implant, and alignment factors associated with revision of medial compartment unicondylar arthroplasty. J Arthroplasty 21(6 Suppl 2):108–115
29. Conteduca F, Iorio R, Mazza D, Ferretti A (2014) Patient-specific instruments in total knee arthroplasty. Int Orthop 38(2):259–265
30. Coon T, Roche M, Pearle AD, Dounchis J, Borus T, Buechel Jr F (2013) Two year survivorship of robotically guided unicompartmental knee arthroplasty. Paper presented at the ISTA 26th annual congress, Palm Beach, FL, USA
31. 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
32. Decking R, Markmann Y, Mattes T, Puhl W, Scharf HP (2007) On the outcome of computer-assisted total knee replacement. Acta Chir Orthop Traumatol Cech 74(3):171–174
33. Dobzyniak M, Fehring TK, Odum S (2006) Early failure in total hip arthroplasty. Clin Orthop Relat Res 447:76–78
34. Dunbar NJ, Roche MW, Park BH, Branch SH, Conditt MA, Banks SA (2012) Accuracy of dynamic tactile-guided unicompartmental knee arthroplasty. J Arthroplasty 27(5):803–808
35. Eagar P, Hull ML, Howell SM (2004) How the fixation method stiffness and initial tension affect anterior load-displacement of the knee and tension in anterior cruciate ligament grafts: a study in cadaveric knees using a double-loop hamstrings graft. J Orthop Res 22(3):613–624
36. Ek ET, Dowsey MM, Tse LF, Riazi A, Love BR, Stoney JD, Choong PF (2008) Comparison of functional and radiological outcomes after computer-assisted versus conventional total knee arthroplasty: a matched-control retrospective study. J Orthop Surg (Hong Kong) 16(2):192–196
37. Fehring TK, Odum S, Griffin WL, Mason JB, Nadaud M (2001) Early failures in total knee arthroplasty. Clin Orthop Relat Res 392:315–318
38. Fricka KB, Sritulanondha S, McAsey CJ (2015) To cement or not? Two-year results of a prospective, randomized study comparing cemented vs. cementless total knee arthroplasty (TKA). J Arthroplasty 30(9 Suppl):55–58
39. Fu Y, Wang M, Liu Y, Fu Q (2012) Alignment outcomes in navigated total knee arthroplasty: a meta-analysis. Knee Surg Sports Traumatol Arthrosc 20(6):1075–1082
40. Gioe TJ, Killeen KK, Grimm K, Mehle K, Scheltema K (2004) Why are total knee replacements revised? Clin Orthop Relat Res 428:100–106
41. Gøthesen O, Espehaug B, Havelin L, Petursson G, Furnes O (2011) Short-term outcome of 1,465 computer-navigated primary total knee replacements 2005–2008. Acta Orthop 82(3):293–300
42. Hansen DC, Kusuma SK, Palmer RM, Harris KB (2014) Robotic guidance does not improve component position or short-term outcome in medial unicompartmental knee arthroplasty. J Arthroplasty 29(9):1784–1789
43. Harvie P, Sloan K, Beaver RJ (2012) Computer navigation vs conventional total knee arthroplasty. Five-year functional results of a prospective randomized trial. J Arthroplasty 27(5):667–672
44. Hasegawa M, Yoshida K, Wakabayashi H, Sudo A (2011) Minimally invasive total knee arthroplasty: comparison of jig-based technique versus computer navigation for clinical and alignment outcome. Knee Surg Sports Traumatol Arthrosc 19(6):904–910
45. Hernández-Vaquero D, Suarez-Vazquez A, Iglesias-Fernandez S (2011) Can computer assistance improve the clinical and functional scores in total knee arthroplasty? Clin Orthop Relat Res 469(12):3436–3442
46. Hetaimish BM, Khan MM, Simunovic N, Al-Harbi HH, Bhandari M, Zalzal PK (2012) Meta-analysis of navigation vs conventional total knee arthroplasty. J Arthroplasty 27(6):1177–1182
47. Hoppe S, Mainzer JD, Frauchiger L, Ballmer PM, Hess R, Zumstein MA (2012) More accurate component alignment in navigated total knee arthroplasty has no clinical benefit at 5-year follow-up. Acta Orthop 83(6):629–633
48. Huang NF, Dowsey MM, Ee E, Stoney JD, Babazadeh S, Choong PF (2012) Coronal alignment correlates with outcome after total knee arthroplasty: five-year follow-up of a randomized controlled trial. J Arthroplasty 27(9):1737–1741
49. Huang TW, Lee CY, Lin SJ, Peng KT, Huang KC, Lee MS, Hsu RW, Shen WJ (2014) Comparison of computer-navigated and conventional total knee arthroplasty in patients with Ranawat type-II valgus deformity: medium-term clinical and radiological results. BMC Musculoskelet Disord 15:390
50. Jeffery RS, Morris RW, Denham RA (1991) Coronal alignment after total knee replacement. J Bone Joint Surg Br 73(5):709–714
51. Ji HM, Han J, Jin DS, Seo H, Won YY (2016) Kinematically aligned TKA can align knee joint line to horizontal. Knee Surg Sports Traumatol Arthrosc 24(8):2436–2441
52. Kamat YD, Aurakzai KM, Adhikari AR, Matthews D, Kalairajah Y, Field RE (2009) Does computer navigation in total knee arthroplasty improve patient outcome at midterm follow-up? Int Orthop 33(6):1567–1570
53. Kendrick BJ, Kaptein BL, Valstar ER, Gill HS, Jackson WF, Dodd CA, Price AJ, Murray DW (2015) Cemented versus cementless Oxford unicompartmental knee arthroplasty using radiostereometric analysis: a randomised controlled trial. Bone Joint J 97-B(2):185–191
54. Khamaisy S, Zuiderbaan HA, van der List JP, Nam D, Pearle AD (2016) Medial unicompartmental knee arthroplasty improves congruence and restores joint space width of the lateral compartment. Knee 23(3):501–505
55. Kim SM, Park YS, Ha CW, Lim SJ, Moon YW (2012) Robot-assisted implantation improves the precision of component position in minimally invasive TKA. Orthopedics 35(9):e1334–e1339
56. Kim TK, Chang CB, Kang YG, Chung BJ, Cho HJ, Seong SC (2010) Execution accuracy of bone resection and implant fixation in computer assisted minimally invasive total knee arthroplasty. Knee 17(1):23–28
57. Kim YH, Park JW, Kim JS (2012) Computer-navigated versus conventional total knee arthroplasty: a prospective randomized trial. J Bone Joint Surg Am 94(22):2017–2024

58. Kim YH, Park JW, Kim JS, Park SD (2014) The relationship between the survival of total knee arthroplasty and postoperative coronal, sagittal and rotational alignment of knee prosthesis. Int Orthop 38(2):379–385
59. Konyves A, Willis-Owen CA, Spriggins AJ (2010) The long-term benefit of computer-assisted surgical navigation in unicompartmental knee arthroplasty. J Orthop Surg Res 5:94
60. Koulalis D, O'Loughlin PF, Plaskos C, Kendoff D, Cross MB, Pearle AD (2011) Sequential versus automated cutting guides in computer-assisted total knee arthroplasty. Knee 18(6):436–442
61. Labek G, Sekyra K, Pawelka W, Janda W, Stockl B (2011) Outcome and reproducibility of data concerning the Oxford unicompartmental knee arthroplasty: a structured literature review including arthroplasty registry data. Acta Orthop 82(2):131–135
62. Lee WT, Chin PL, Lo NN, Yeo SJ (2015) Short-term outcome after computer-assisted versus conventional total knee arthroplasty: a randomised controlled trial. J Orthop Surg (Hong Kong) 23(1):71–75
63. Lehnen K, Giesinger K, Warschkow R, Porter M, Koch E, Kuster MS (2011) Clinical outcome using a ligament referencing technique in CAS versus conventional technique. Knee Surg Sports Traumatol Arthrosc 19(6):887–892
64. Lin SY, Chen CH, Fu YC, Huang PJ, Lu CC, Su JY, Chang JK, Huang HT (2013) Comparison of the clinical and radiological outcomes of three minimally invasive techniques for total knee replacement at two years. Bone Joint J 95(7):906–910
65. Liow MH, Xia Z, Wong MK, Tay KJ, Yeo SJ, Chin PL (2014) Robot-assisted total knee arthroplasty accurately restores the joint line and mechanical axis. A prospective randomised study. J Arthroplasty 29(12):2373–2377
66. Liow MHL, Chin PL, Tay KJD, Chia SL, Lo NN, Yeo SJ (2014) Early experiences with robot-assisted total knee arthroplasty using the digiMatch™ ROBODOC® surgical system. Singapore Med J 55(10):529–534
67. Lonner JH (2009) Robotic arm-assisted unicompartmental arthroplasty. Semin Arthroplasty 20(1):15–22
68. Lonner JH, John TK, Conditt MA (2010) Robotic arm-assisted UKA improves tibial component alignment: a pilot study. Clin Orthop Relat Res 468(1):141–146
69. Lonner JH, Smith JR, Picard F, Hamlin B, Rowe PJ, Riches PE (2015) High degree of accuracy of a novel image-free handheld robot for unicondylar knee arthroplasty in a cadaveric study. Clin Orthop Relat Res 473(1):206–212
70. Luring C, Kauper M, Bathis H, Perlick L, Beckmann J, Grifka J, Tingart M, Rath B (2012) A five to seven year follow-up comparing computer-assisted vs freehand TKR with regard to clinical parameters. Int Orthop 36(3):553–558
71. Lutzner J, Dexel J, Kirschner S (2013) No difference between computer-assisted and conventional total knee arthroplasty: five-year results of a prospective randomised study. Knee Surg Sports Traumatol Arthrosc 21(10):2241–2247
72. MacCallum KP, Danoff JR, Geller JA (2016) Tibial baseplate positioning in robotic-assisted and conventional unicompartmental knee arthroplasty. Eur J Orthop Surg Traumatol 26(1):93–98
73. Manzotti A, Cerveri P, Pullen C, Confalonieri N (2014) Computer-assisted unicompartmental knee arthroplasty using dedicated software versus a conventional technique. Int Orthop 38(2):457–463
74. Mason JB, Fehring TK, Estok R, Banel D, Fahrbach K (2007) Meta-analysis of alignment outcomes in computer-assisted total knee arthroplasty surgery. J Arthroplasty 22(8):1097–1106
75. Matziolis G, Krocker D, Weiss U, Tohtz S, Perka C (2007) 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 89(2):236–243
76. Meijer MF, Reininga IH, Boerboom AL, Bulstra SK, Stevens M (2014) Does imageless computer-assisted TKA lead to improved rotational alignment or fewer outliers? A systematic review. Clin Orthop Relat Res 472(10):3124–3133
77. Moher D, Liberati A, Tetzlaff J, Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 6(7):e1000097
78. Molfetta L, Caldo D (2008) Computer navigation versus conventional implantation for varus knee total arthroplasty: a case-control study at 5 years follow-up. Knee 15(2):75–79
79. Mont MA, Pivec R, Issa K, Kapadia BH, Maheshwari A, Harwin SF (2014) Long-term implant survivorship of cementless total knee arthroplasty: a systematic review of the literature and meta-analysis. J Knee Surg 27(5):369–376
80. Moon YW, Ha CW, Do KH, Kim CY, Han JH, Na SE, Lee CH, Kim JG, Park YS (2012) Comparison of robot-assisted and conventional total knee arthroplasty: a controlled cadaver study using multiparameter quantitative three-dimensional CT assessment of alignment. Comput Aided Surg 17(2):86–95
81. Moskal JT, Capps SG, Mann JW, Scanelli JA (2014) Navigated versus conventional total knee arthroplasty. J Knee Surg 27(3):235–248
82. Mueller JK, Wentorf FA, Moore RE (2014) Femoral and tibial insert downsizing increases the laxity envelope in TKA. Knee Surg Sports Traumatol Arthrosc 22(12):3003–3011
83. Nair R, Tripathy G, Deysine GR (2014) Computer navigation systems in unicompartmental knee arthroplasty: a systematic review. Am J Orthop (Belle Mead NJ) 43(6):256–261
84. Nam D, McArthur BA, Cross MB, Pearle AD, Mayman DJ, Haas SB (2012) Patient-specific instrumentation in total knee arthroplasty: a review. J Knee Surg 25(3):213–219
85. National Joint Registry for England, Wales, Northern Ireland and the Isle of Man (2015) 12th Annual report
86. Nedopil AJ, Howell SM, Hull ML (2016) Does malrotation of the tibial and femoral components compromise function in kinematically aligned total knee arthroplasty? Orthop Clin North Am 47(1):41–50
87. The New Zealand Joint Registry (2014) Fourteen year report. January 1999 to December 2013
88. Niinimaki TT, Murray DW, Partanen J, Pajala A, Leppilahti JI (2011) Unicompartmental knee arthroplasties implanted for osteoarthritis with partial loss of joint space have high re-operation rates. Knee 18(6):432–435
89. Pabinger C, Berghold A, Boehler N, Labek G (2013) Revision rates after knee replacement. Cumulative results from worldwide clinical studies versus joint registers. Osteoarthr Cartil 21(2):263–268
90. Pagnano MW, Hanssen AD, Lewallen DG, Stuart MJ (1998) Flexion instability after primary posterior cruciate retaining total knee arthroplasty. Clin Orthop Relat Res 356:39–46
91. Pandit H, Jenkins C, Gill HS, Barker K, Dodd CA, Murray DW (2011) Minimally invasive Oxford phase 3 unicompartmental knee replacement: results of 1000 cases. J Bone Joint Surg Br 93(2):198–204
92. Pang HN, Yeo SJ, Chong HC, Chin PL, Ong J, Lo NN (2011) Computer-assisted gap balancing technique improves outcome in total knee arthroplasty, compared with conventional measured resection technique. Knee Surg Sports Traumatol Arthrosc 19(9):1496–1503
93. Park SE, Lee CT (2007) Comparison of robotic-assisted and conventional manual implantation of a primary total knee arthroplasty. J Arthroplasty 22(7):1054–1059

94. Pearle AD, O'Loughlin PF, Kendoff DO (2010) Robot-assisted unicompartmental knee arthroplasty. J Arthroplasty 25(2):230–237
95. Plate JF, Mofidi A, Mannava S, Smith BP, Lang JE, Poehling GG, Conditt MA, Jinnah RH (2013) Achieving accurate ligament balancing using robotic-assisted unicompartmental knee arthroplasty. Adv Orthop 2013:837167
96. Rand JA, Coventry MB (1988) Ten-year evaluation of geometric total knee arthroplasty. Clin Orthop Relat Res 232:168–173
97. Rebal BA, Babatunde OM, Lee JH, Geller JA, Patrick DA Jr, Macaulay W (2014) Imageless computer navigation in total knee arthroplasty provides superior short term functional outcomes: a meta-analysis. J Arthroplasty 29(5):938–944
98. Ritter MA, Faris PM, Keating EM, Meding JB (1994) Postoperative alignment of total knee replacement. Its effect on survival. Clin Orthop Relat Res 299:153–156
99. Roberts TD, Clatworthy MG, Frampton CM, Young SW (2015) Does computer assisted navigation improve functional outcomes and implant survivability after total knee arthroplasty? J Arthroplasty 30(9):59–63
100. Roche M, Elson L, Anderson C (2014) Dynamic soft tissue balancing in total knee arthroplasty. Orthop Clin North Am 45(2):157–165
101. Rosskopf J, Singh PK, Wolf P, Strauch M, Graichen H (2014) Influence of intentional femoral component flexion in navigated TKA on gap balance and sagittal anatomy. Knee Surg Sports Traumatol Arthrosc 22(3):687–693
102. Ryd L, Lindstrand A, Stenström A, Selvik G (1990) Porous coated anatomic tricompartmental tibial components: the relationship between prosthetic position and micromotion. Clin Orthop Relat Res 251:189–197
103. Schmitt J, Hauk C, Kienapfel H, Pfeiffer M, Efe T, Fuchs-Winkelmann S, Heyse TJ (2011) Navigation of total knee arthroplasty: rotation of components and clinical results in a prospectively randomized study. BMC Musculoskelet Disord 12:16
104. Schnurr C, Güdden I, Eysel P, König DP (2012) Influence of computer navigation on TKA revision rates. Int Orthop 36(11):2255–2260
105. Seon JK, Song EK, Park SJ, Yoon TR, Lee KB, Jung ST (2009) Comparison of minimally invasive unicompartmental knee arthroplasty with or without a navigation system. J Arthroplasty 24(3):351–357
106. Shi J, Wei Y, Wang S, Chen F, Wu J, Huang G, Chen J, Wei L, Xia J (2014) Computer navigation and total knee arthroplasty. Orthopedics 37(1):e39–e43
107. Siebert W, Mai S, Kober R, Heeckt PF (2002) Technique and first clinical results of robot-assisted total knee replacement. Knee 9(3):173–180
108. Sierra RJ, Kassel CA, Wetters NG, Berend KR, Della Valle CJ, Lombardi AV (2013) Revision of unicompartmental arthroplasty to total knee arthroplasty: not always a slam dunk! J Arthroplasty 28(8 Suppl):128–132
109. Singh VK, Varkey R, Trehan R, Kamat Y, Raghavan R, Adhikari A (2012) Functional outcome after computer-assisted total knee arthroplasty using measured resection versus gap balancing techniques: a randomised controlled study. J Orthop Surg (Hong Kong) 20(3):344–347
110. Sinha RK (2009) Outcomes of robotic arm-assisted unicompartmental knee arthroplasty. Am J Orthop (Belle Mead NJ) 38(2 Suppl):20–22
111. Smith JR, Riches PE, Rowe PJ (2014) Accuracy of a freehand sculpting tool for unicondylar knee replacement. Int J Med Robot 10(2):162–169
112. Song EK, Mohite N, Lee SH, Na BR, Seon JK (2015) Comparison of outcome and survival after unicompartmental knee arthroplasty between navigation and conventional techniques with an average 9-year follow-up. J Arthroplasty 31(2):395–400
113. Song EK, Seon JK, Park SJ, Jung WB, Park HW, Lee GW (2011) Simultaneous bilateral total knee arthroplasty with robotic and conventional techniques: a prospective, randomized study. Knee Surg Sports Traumatol Arthrosc 19(7):1069–1076
114. Song EK, Seon JK, Yim JH, Netravali NA, Bargar WL (2013) Robotic-assisted TKA reduces postoperative alignment outliers and improves gap balance compared to conventional TKA. Clin Orthop Relat Res 471(1):118–126
115. Spencer JM, Chauhan SK, Sloan K, Taylor A, Beaver RJ (2007) Computer navigation versus conventional total knee replacement: no difference in functional results at two years. J Bone Joint Surg Br 89(4):477–480
116. Sriphirom P, Raungthong N, Chutchawan P, Thiranon C, Sukandhavesa N (2012) Influence of a secondary downsizing of the femoral component on the extension gap: a cadaveric study. Orthopedics 35(10 Suppl):56–59
117. Stiehl JB, Heck DA (2015) How precise is computer-navigated gap assessment in TKA? Clin Orthop Relat Res 473(1):115–118
118. Stulberg SD, Yaffe MA, Koo SS (2006) Computer-assisted surgery versus manual total knee arthroplasty: a case-controlled study. J Bone Joint Surg Am 88(Suppl 4):47–54
119. Thiengwittayaporn S, Kanjanapiboonwong A, Junsee D (2013) Midterm outcomes of electromagnetic computer-assisted navigation in minimally invasive total knee arthroplasty. J Orthop Surg Res 8:37
120. Thienpont E, Fennema P, Price A (2013) Can technology improve alignment during knee arthroplasty. Knee 20:S21–S28
121. Tolk JJ, Koot HW, Janssen RP (2012) Computer navigated versus conventional total knee arthroplasty. J Knee Surg 25(4):347–352
122. van der List JP, Chawla H, Pearle AD (2016) Robotic-assisted knee arthroplasty: an overview. Am J Orthop (Belle Mead NJ) 45(4):202–211
123. van der List JP, Chawla H, Villa JC, Zuiderbaan HA, Pearle AD (2015) Early functional outcome after lateral UKA is sensitive to postoperative lower limb alignment. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-015-3877-0
124. van der List JP, Chawla H, Zuiderbaan HA, Pearle AD (2016) Patient selection criteria for unicompartmental knee arthroplasty: a meta-analysis critique. J Arthroplasty. doi:10.1016/j.arth.2016.04.001
125. van der List JP, McDonald LS, Pearle AD (2015) Systematic review of medial versus lateral survivorship in unicompartmental knee arthroplasty. Knee 22(6):454–460
126. van der List JP, Zuiderbaan HA, Pearle AD (2016) Why do medial unicompartmental knee arthroplasties fail today? J Arthroplasty 31(5):1016–1021
127. van Strien T, van der Linden-van der Zwaag E, Kaptein B, van Erkel A, Valstar E, Nelissen R (2009) Computer assisted versus conventional cemented total knee prostheses alignment accuracy and micromotion of the tibial component. Int Orthop 33 (5):1255–1261
128. Vasso M, Del Regno C, D'Amelio A, Viggiano D, Corona K, Schiavone Panni A (2015) Minor varus alignment provides better results than neutral alignment in medial UKA. Knee 22(2):117–121
129. Wasielewski RC, Galante JO, Leighty RM, Natarajan RN, Rosenberg AG (1994) Wear patterns on retrieved polyethylene tibial inserts and their relationship to technical considerations during total knee arthroplasty. Clin Orthop Relat Res 299:31–43
130. Weber P, Crispin A, Schmidutz F, Utzschneider S, Pietschmann MF, Jansson V, Muller PE (2013) Improved accuracy in computer-assisted unicondylar knee arthroplasty: a meta-analysis. Knee Surg Sports Traumatol Arthrosc 21(11):2453–2461

131. Weber P, Utzschneider S, Sadoghi P, Pietschmann MF, Ficklscherer A, Jansson V, Müller PE (2012) Navigation in minimally invasive unicompartmental knee arthroplasty has no advantage in comparison to a conventional minimally invasive implantation. Arch Orthop Trauma Surg 132(2):281–288
132. Whiteside LA (2005) Making your next unicompartmental knee arthroplasty last. J Arthroplasty 20:2–3
133. Wright JG, Swiontkowski MF, Heckman JD (2003) Introducing levels of evidence to the journal. J Bone Joint Surg Am 85(1):1–3
134. Yaffe M, Chan P, Goyal N, Luo M, Cayo M, Stulberg SD (2013) Computer-assisted versus manual TKA: no difference in clinical or functional outcomes at 5-year follow-up. Orthopedics 36(5):e627–e632
135. Yang JH, Yoon JR, Pandher DS, Oh KJ (2010) Clinical and radiologic outcomes of contemporary 3 techniques of TKA. Orthopedics 33(10 Suppl):76–81
136. Yildirim G, Fernandez-Madrid I, Schwarzkopf R, Walker PS, Karia R (2014) Comparison of robot surgery modular and total knee arthroplasty kinematics. J Knee Surg 27(2):157–163
137. Yoshida K, Tada M, Yoshida H, Takei S, Fukuoka S, Nakamura H (2013) Oxford phase 3 unicompartmental knee arthroplasty in Japan—clinical results in greater than one thousand cases over ten years. J Arthroplasty 28(9 Suppl):168–171
138. Young SW, Clarke HD, Graves SE, Liu YL, de Steiger RN (2015) Higher rate of revision in PFC sigma primary total knee arthroplasty with mismatch of femoro-tibial component sizes. J Arthroplasty 30(5):813–817
139. Zamora LA, Humphreys KJ, Watt AM, Forel D, Cameron AL (2013) Systematic review of computer-navigated total knee arthroplasty. ANZ J Surg 83(1–2):22–30
140. Zhang Z, Gu B, Zhu W, Zhu L, Li Q, Du Y (2014) Minimally invasive and computer-assisted total knee arthroplasty versus conventional technique: a prospective, randomized study. Eur J Orthop Surg Traumatol 24(8):1475–1479
141. Zhang Z, Zhu W, Zhu L, Du Y (2014) Superior alignment but no difference in clinical outcome after minimally invasive computer-assisted unicompartmental knee arthroplasty (MICA-UKA). Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3456-9
142. Zhu M, Ang CL, Yeo SJ, Lo NN, Chia SL, Chong HC (2015) Minimally invasive computer-assisted total knee arthroplasty compared with conventional total knee arthroplasty: a prospective 9-year follow-up. J Arthroplasty 31(5):1000–1004
143. Zihlmann MS, Stacoff A, Romero J, Quervain IK, Stussi E (2005) Biomechanical background and clinical observations of rotational malalignment in TKA: literature review and consequences. Clin Biomech (Bristol, Avon) 20(7):661–668
144. Zuiderbaan HA, Khamaisy S, Thein R, Nawabi DH, Pearle AD (2015) Congruence and joint space width alterations of the medial compartment following lateral unicompartmental knee arthroplasty. Bone Joint J 97(1):50–55