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KNEE ARTHROPLASTY

Bi-cruciate retaining total knee arthroplasty: a systematic literature review of clinical outcomes

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Abstract

Total knee arthroplasty (TKA) has been shown to have good long-term outcomes and survivorship. Nonetheless, dissatisfied patients are frequently reported in the literature. Bi-cruciate retaining total knee prostheses (BCR TKA) were designed to address the demand for more kinematically functional implants that better reconstruct natural knee kinematics. In BCR TKA, the anterior cruciate ligament (ACL) is preserved. Improved patient-reported outcomes and satisfaction levels are expected. This review aimed to summarize indications for and clinical outcomes of BCR TKA. A systematic literature review on BCR TKA was performed. 24 articles were included for data analysis. Indications covered osteoarthritis, inflammatory arthritis and others. The degree of deformity was often but not always limited to minor axial deformity and contractures: maximum acceptable varus/valgus deformity reached 10°–30° and flexion contractures of 15°–65°. ACL intactness was macroscopically examined intraoperatively in nine studies and clinically tested in ten studies (e.g., Lachmann Test, drawer-test). Objective and patient-reported outcome scores were reported for follow-up periods of up to 22 years. Survival rates varied significantly. For first generation implants, 22-year survival reached 82% while a second generation design was associated with 13.5% revision rate at 18 months. Reasons for varying outcomes were not clear and may be attributed to the implant itself, surgical techniques and patient specific variables including changed expectations and functional demand. The literature has not shown clear indications and guidelines for the use of BCR implants. The promising results of first generation BCR TKA designs may be optimized through improved implant designs in the future. Further studies are advocated to provide the necessary evidence of second generation BCR TKA designs.

Keywords Total knee arthroplasty · Anterior cruciate ligament · Osteoarthritis · Joint replacement · Systematic review

Abbreviations

ACL	Anterior cruciate ligament
BCR	Bi-cruciate retaining total knee arthroplasty
BMI	Body mass index
CR	Cruciate retaining
FU	Follow-up
KSS	Knee Society Score
OA	Osteoarthritis
PE	Polyethylene
PCL	Posterior cruciate ligament
PS	Posterior stabilized
ROM	Range of motion
TKA	Total knee arthroplasty
UKA	Unicondylar knee arthroplasty

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Introduction

Joint replacement with total knee arthroplasty (TKA) is growing in most countries [28]. In the United States alone, 226 people per 100,000 of the population received a TKA in 2015. The corresponding number in the OECD countries is over 140 per 100,000 [28]. Demographic changes and a growing number of younger patients are expanding the numbers of patients undergoing TKA. Higher expectations and functional demands have been observed in this expanded patient population [7, 12]. Although new TKA technologies are being constantly introduced, there is still a significant number of unsatisfied patients after TKA [18, 34, 44].

For primary TKA, cruciate retaining (CR) or posterior stabilized (PS) designs are usually used. Both designs sacrifice the anterior cruciate ligament (ACL) and both show promising long-term results with low revision-rates [1, 10]. However, patient-reported outcome measures indicate significant numbers of unsatisfied patients [18, 34]. Possible reasons for dissatisfaction are altered kinematics including paradoxical anterior femoral translation and reduced proprioception after TKA [22]. The ACL has been shown to be a relevant factor for optimal knee kinematics and allows for several particular mechanisms in knee movement, the posterior rollback of the femur during flexion being one [16, 43]. Additionally, the ACL's proprioceptive qualities may play a significant role in natural movement [30]. Therefore, preservation of an intact ACL in knee replacement may help to improve functional outcomes.

Bi-cruciate retaining (BCR) TKA implants preserving both the anterior and the posterior cruciate ligament (PCL) were already developed in the early stages of TKA [13]. In the 1960s, various approaches to BCR knees were introduced. Horseshoe designs of the tibia component allowed for retention of the ACL. While early designs had comparable long-term outcomes to early CR and PS designs, they were replaced over the decades [9, 20, 40]. At least two new BCR implants were introduced to the market in the last 20 years. However, the perceived demanding procedure and mixed clinical results led to the withdrawal or limited use of most implants [31, 45]. The recent novel designs of BCR TKA require clinical evidence to determine effectiveness and survivorship [6, 17, 23].

This systematic literature review aims to summarize the indications and the published clinical outcomes of BCR TKA.

Material and methods

Pilot search strategy

A pilot literature search on Medline via PubMed was performed in June 2018 to identify possible search terms for BCR TKA. Based on the results, a comprehensive search strategy was developed. The initial search for "anterior cruciate ligament osteoarthritis joint replacement" yielded 204 hits. Based on the titles of articles, further keywords were identified and entered into the next search. This process was repeated until no additional hits (without duplicates) were found. For each identified article, the PubMed function "similar articles" was used and additional articles were added to the algorithm.

Literature search strategy

A comprehensive search of the literature using PubMed and EMBASE was performed in November 2019. The following keywords were used: "anterior retention arthroplasty", "acl preserving knee replacement", "acl retaining knee replacement", "acl retaining knee arthroplasty", "bcr knee", "bicruciate preserving", "bi-cruciate preserving", "bicruciate retaining", "bi-cruciate retaining" and "bicruciate retention". No restrictions were imposed and all fields were searched.

The exact search strategy was:

> "anterior retention arthroplasty OR acl preserving knee replacement OR acl retaining knee replacement OR acl retaining knee arthroplasty OR bcr knee OR bicruciate preserving OR bi-cruciate preserving OR bicruciate retaining OR bi-cruciate retaining OR bicruciate retention"
>
> "(anterior [All Fields] AND ("retention (psychology)" [MeSH Terms] OR ("retention" [All Fields] AND "(psychology)" [All Fields]) OR "retention (psychology)" [All Fields] OR "retention" [All Fields]) AND ("arthroplasty" [MeSH Terms] OR "arthroplasty" [All Fields])) OR (("anterior cruciate ligament" [MeSH Terms] OR ("anterior" [All Fields] AND "cruciate" [All Fields] AND "ligament" [All Fields]) OR "anterior cruciate ligament" [All Fields] OR "acl" [All Fields]) AND preserving [All Fields] AND ("arthroplasty, replacement, knee" [MeSH Terms] OR ("arthroplasty" [All Fields] AND "replacement" [All Fields] AND "knee" [All Fields]) OR "knee replacement arthroplasty" [All Fields] OR ("knee" [All Fields] AND "replacement" [All Fields]) OR "knee replacement" [All Fields])) OR (("anterior cruciate ligament" [MeSH Terms] OR ("anterior" [All Fields] AND "cruciate" [All Fields] AND "ligament" [All Fields]) OR "anterior cruciate ligament" [All Fields] OR "acl" [All Fields]) AND retaining [All Fields] AND ("arthroplasty, replacement, knee" [MeSH Terms] OR ("arthroplasty" [All Fields] AND "replacement" [All Fields] AND "knee" [All Fields]) OR "knee replacement arthroplasty" [All Fields] OR ("knee" [All Fields] AND "replacement" [All Fields]) OR "knee replacement" [All Fields])) OR (("anterior cruciate ligament" [MeSH Terms] OR ("anterior" [All Fields] AND "cruciate" [All Fields] AND "ligament" [All Fields]) OR "anterior cruciate ligament" [All Fields] OR "acl" [All Fields]) AND retaining [All Fields] AND ("arthroplasty, replacement, knee" [MeSH Terms] OR ("arthroplasty" [All Fields] AND "replacement" [All Fields] AND "knee" [All Fields]) OR "knee replacement arthroplasty" [All Fields] OR ("knee" [All Fields] AND "arthroplasty" [All Fields])

OR "knee arthroplasty" [All Fields])) OR (("Breast Cancer Res" [Journal] OR "bcr" [All Fields]) AND ("knee" [MeSH Terms] OR "knee" [All Fields] OR "knee joint" [MeSH Terms] OR ("knee" [All Fields] AND "joint" [All Fields]) OR "knee joint" [All Fields])) OR (bicruciate [All Fields] AND preserving [All Fields]) OR (bi-cruciate [All Fields] AND preserving [All Fields]) OR (bicruciate [All Fields] AND retaining [All Fields]) OR (bi-cruciate [All Fields] AND retaining [All Fields]) OR (bicruciate [All Fields] AND ("retention (psychology)" [MeSH Terms] OR ("retention" [All Fields] AND "(psychology)" [All Fields]) OR "retention (psychology)" [All Fields] OR "retention" [All Fields]))"

Inclusion/exclusion criteria

Inclusion criteria were original articles with clinical data on patients receiving BCR TKA (clinical outcome scores and/or survival/revision data). Exclusion criteria were: (1) review articles, (2) gray literature (e.g., conference abstracts), editorials or letters, (3) non-English or non-German language articles, (4) original articles on non-BCR arthroplasty, (5) articles without TKA patients, (6) case reports, (7) articles not about the knee, (8) non-human studies, (9) non-clinical studies and, (10) kinematic studies without clinical outcome data.

All titles and abstracts were screened using inclusion and exclusion criteria. Of 422 identified articles, 345 publications were excluded during the screening process for not meeting either one or multiple of the inclusion criteria or meeting one or multiple exclusion criteria. 77 Full texts of all eligible articles were retrieved and analysed in detail by the primary author. Clinical studies with outcome measures were included.

Extraction and analysis of data

For all included studies, the complete citation, publication year, study design, implant type, number of patients and knees per group, sex distributions, patient age (mean, range, SD), body mass index (BMI) and comments with additional relevant information were collected. Information on indications (etiology, deformity, contractures, other relevant items), macroscopic appearance and clinical function of the ACL, follow-up (FU) time, revision rates, survival rates, function scores, range of motion (ROM), clinical stability and patient preferences were additionally collected. 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) guidelines were adhered to while conducting the literature search strategy, as well as data analysis and extraction.

BCR TKA systems were stratified into first or second generation to improve readability. Two systems more recently introduced into the market were defined as second generation (Vanguard™ XP, JOURNEY II™ XR), while all other were defined as first generation. Given the complexity of TKA design evolution, this is a simplified system.

Results

Overall, 422 studies were identified (Fig. 1). Of these, twenty-four studies reported on clinical outcome parameters and were included in the analysis [2, 3, 5, 6, 8, 11, 13, 14, 19–21, 24–27, 31, 32, 35–38, 40, 42, 45]. All included articles are presented in Table 1 with baseline information on the publication. Two reports on the same cohort by Kono et al. and two reports by Peng et al. and Arauz et al. were each combined into one study [3, 24, 25, 32].

There were no randomized controlled trials (Level I studies). A total of 1,806 knees in 24 studies were reported (due to multiple reports on similar cohorts, the absolute number of cases might be lower). The follow-up means ranged from 7.7 months to 23 years. Six different BCR implant types were used (see "Appendix" for further information). 14 studies compared the BCR TKA to another TKA system and/or unicondylar knee arthroplasty (UKA).

Indications for BCR implantation

Fifteen publications included information on indications for BCR TKA implantation (Table 2).

Ten publications reported on varus and valgus deformity before surgery. Baumann and Pritchett (3 publications) mentioned strict limitations of 10° and 15° valgus deformity and 10° and 20° valgus deformity, [5, 35–37] respectively. Christensen indicated that minimal deformity is acceptable [11]. Cloutier included valgus deformities of up to 20° (16% of cases) and varus deformities of up to 30° (67%) while 17% showed a "normal alignment" between 0° varus and 10° valgus [14]. In another publication by Cloutier, valgus of 30° was accepted as well [13].

Five publications mentioned flexion contractures [14]. Christensen limited BCR indications to "minimal" contracture, [11] while Lavoie and Pritchett were less restrictive [26, 38]. Cloutier did not restrict indications and reported surgery in cases with 25°–65° contracture in 16 knees [14]. No systematic analysis with regard to the clinical outcomes for these cases was performed.

Second generation BCR TKA were associated with a more restrictive indication spectrum.

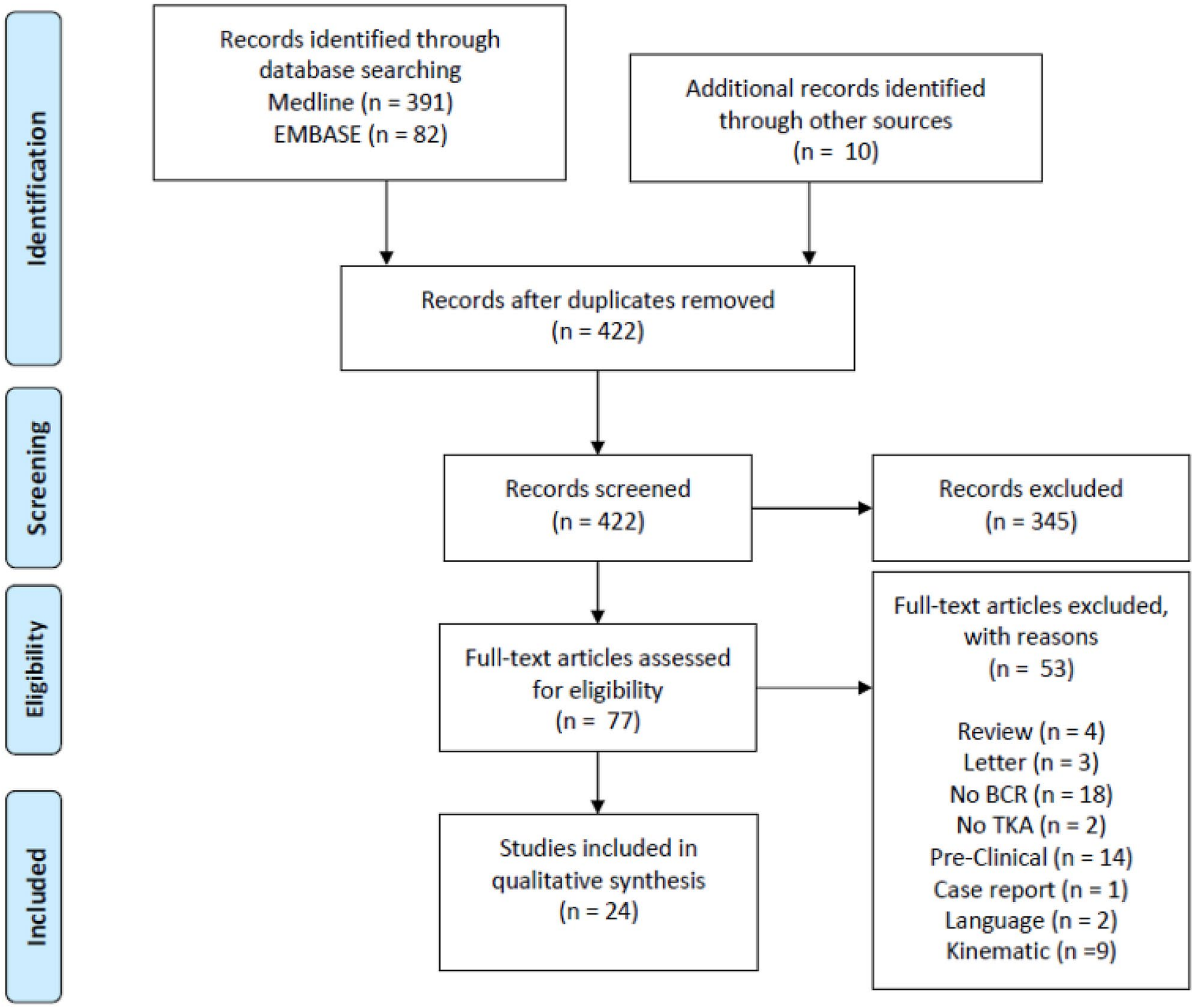

Fig. 1 Modified PRISMA flow-chart

ACL status

15 studies indicated the status of the ACL before or during surgery (Table 3). Nine reports mentioned macroscopic assessment during surgery [2, 11, 13, 14, 20, 31, 36, 38, 40]. Sabouret et al. specifically accepted varying degrees of degeneration [40]. In ten publications, a clinical function test was applied to determine the functional status of the ACL [11, 13, 14, 21, 26, 31, 36, 38, 40, 45]. Seven of these publications specified the test and/or time of testing. Only one study by Pritchett mentioned the history of ACL injuries as a parameter for decision-making [35]. Kono et al. used a pre-operative MRI to identify the integrity of the ACL [24]. Pelt et al. used X-ray signs to indirectly assess the ACL status [31]. There were no relevant differences between first and second generation systems except for the two studies using imaging data pre-operatively for second generation implants.

Outcome measures

All studies showed an improvement in the Knee Society Score (KSS) (Table 4). Pre-operative scores were low in all studies. Range of motion (flexion) showed mixed results. Some studies showed lower mean ROM post-surgery compared to pre-operative measurements. The mean ROM (flexion) after surgery was below 110° in 3 studies and below 120° in 11 studies. Four studies showed a mean ROM of more than 120°. Mostly, second generation systems achieved minimally higher mean ROM pre- and post-operatively and no relevant differences in knee scores were observed. In

Table 1 Baseline information on included studies

First author	Year	Study design	Mean age (SD/range) [yrs]	Implant BCR group	n	Male/female	BMI (kg/m^2) mean (SD/range)	Control 1	*n*	Control 2	*n*	Follow-up time mean (SD/range)
First generation*												
Buechel [8]	1990		66 (31–88) ^{CL} 64 (33–88) ^{C}	LCS™	46	n.a	n.a	LCS™ CR	57^{CL}	LCS™ rotating	65^{CL} 43^{C}	6 yrs ^{CL} 12 yrs ^{C}
Cloutier [13]	1991	Pro	59 (31–76)	Cloutier I/Hermes™ 2C ACR [33]	28	n.a	n.a	Hermes™ CR [33]	24			10–13 yrs
Cloutier [14]	2001	Pro	67 (8.6) (all) 67 (8.6) (BCR)	Cloutier I/Hermes™ 2C ACR [33]	163	24/65 patients	n.a		41			10 (9–11) yrs
Jenny [20]	1998	Pro	69 (24–79)	Search™ BCR TKA	32	n.a	n.a	Search™ TKA	93			2–3 yrs
Lavoie [26]	2018	Retro	63 (45–83) vs 67 (43–85)	Hermes™ 2C ACR [33]	100	37/63	n.a	PS (n.a.)	100			18 (5–50) mo BCR 38 (13–71) mo PS
Moro-oka [27]	2007	Retro	n.a	N2C™	9	n.a	n.a	Natural-Knee™	5			71 (4–84) mo BCR 72 (54–96) mo other
Pritchett [35]	1996	Pro	65 (46–78)	Biopro™^{2}	50	19/31	n.a	CR	50			5 yrs min
Pritchett [38]	2004	Pro	66 (BCR)	n.a.^{2} (Biopro™ & WMT)	201	n.a	n.a	MLP	487	PCL, PS (multiple)		7 (2–14) yrs
Pritchett [37]	2013	Pro	n.a	Biopro™^{2}	n.a	n.a	n.a	Multiple	n.a			140.9 mo BCR
Pritchett [36]	2015	Retro	65 (42–84)	Townley Anatomic™^{2}	214	n.a	n.a					23 (20–24) yrs
Sabouret [40]	2013	Pro	83.5 (63–101)	Hermes™ 2C ACR [33]	32	n.a	29.9 (19.6–43.4)					22 yrs
Stiehl [42]	2006	Retro	68 (all) 62 (BCR)	LCS™	324	n.a	n.a	LCS™ CR	2165	LCS™ PS	2254	14 yrs
Second generation*												
Alnachoukati [2] #	2018	Retro	68 (49–82)	Vanguard™ XP	146	43/104	30 (20–40)					12 (1–33) mo
Arauz [3] and Peng [32]^	2019		65.7 (47–76)	Vanguard™ XP	29	14/15	n.a					12.7 (10.9–21.3) mo
Baumann [5]	2017	PCT	62.1 (43–78)	Vanguard™ XP	20	9/11	30	Oxford™ UKA	20	Genesis II	20	8.5 (6–12) mo
Baumann [6]	2018	PCT	62.3 (38–81)	Vanguard™ XP	34	15/19	30	Oxford™ UKA	34	Genesis II	34	18 mo
Christensen [11]	2017	Retro	64 (9) (all) 65 (7) (BCR)	Vanguard™ XP	66	25/41	31 (5)	Vanguard™ CR	237			18 (2–32) mo
Hennessy [19]	2019		65.7 (47–76)	Vanguard™ XP	29	14/15	Male: 30.9 (3.4) Female: 28.7 (4.4)					12.7 (51.1; 3.9–21.3) mo
Kalaai [21]	2019	Retro	65.2 (7.1) BCR 64.4 (7.2) CR	Vanguard™ XP $	61	23/38	27.5 (7.1)	Vanguard™ CR $	61			36 mo

second generation studies, patient reported outcomes were reported with higher frequencies.

Revision rates and survival

In 13 studies, revision rates and/or survival were reported at 8.5 months to 22 years follow-up (Table 5). Eight studies reported short-term follow-up of less than 5 years. Revision rates within short term follow-up ranged from 1 to 13.5%. All second generation studies reported on survival of one implant (Vanguard XP).

Discussion

This literature review aimed to summarize clinical data on bi-cruciate retaining total knee arthroplasty. To our knowledge, this is the first systematic literature review on clinical outcomes of BCR TKA. Previously, only Osmani et al. systematically reviewed the literature. However, they focused on a narrative presentation of the results without structured presentation of their findings [29]. A recent survey showed a strong interest in BCR TKA by orthopaedic surgeons but limited experience and use paired with a perceived lack of guidance on indications [17].

In the present review, 422 studies were identified and screened. Of these, 24 studies could be included in a comprehensive analysis and data summary. The focus was on indications for BCR TKA, examination of the intactness of the anterior cruciate ligament and clinical outcomes including clinical scores and survival/revisions. These findings might help surgeons to understand the indications for BCR TKA and put expectations into perspective of the current literature.

Generally, the critical role of the ACL for kinematics and proprioception of native knee joints has been shown. However, there is a need to prove a clinical benefit of ACL preservation in knee arthroplasty [4, 41]. In particular, the clinical performance of BCR TKA in terms of objective and patient-reported outcomes as well as survivorship is a requirement for acceptance by surgeons and patients. Of note, there is no established system to categorize the designs of BCR TKA. Early BCR TKA designs were developed parallel to other TKA systems [15]. The evolution from the total condylar prosthesis, polycentric geometry (i.e., Townley), anatomic and later the low contact stress included BCR besides CR and PS designs. Throughout the years, the complexity of the TKA evolution grew and many BCR TKA designs was developed [15]. To provide a better overview, a simplified categorization into first and second generation BCR TKA designs was performed. Here, only the two most recent designs were stratified into the second generation.

Table 1 (continued)

First author	Year	Study design	Mean age (SD/range) [yrs]	Implant BCR group	n	Male/female	BMI (kg/m²) mean (SD/range)	Control 1	n	Control 2	n	Follow-up time mean (SD/range)
Kono [24, 25]	2019		71.1 (5.9) BCR 72.8 (7.9) UKA 38.1 (6.1) con	Journey II XR§	17	4:13	n.a	Oxford™ UKA	21	Healthy controls	16	7.7 (1.1) mo BCR 9.8 (2.7) mo UKA
Pelt [31] #	2019	Retro	64 (39–83)	Vanguard™ XP	141	57/84	30.3 (18.8–44.3)					3 (0.34–4.9) yrs
Tsai [45]	2019		65.8 (7.6)	Vanguard™ XP	30	15/15	29.5 (4.3)					12.9 (16.7) mo

Arauz reported KSS at 12 months and Tsai at 6 months; potentially, all publications by Pritchett include similar patient cohorts. Cloutier and Hermes™ BCR TKA seem to be identical following Petit [33] and Komistek [22]; Komistek indicates that Jenny [20] reported on Hermes™ TKA as well (Jenny used Search™)

CCS case control study, *CL* cementless, *C* cemented, *n.a.* not applicable, *PCT* prospective controlled trial, *Pro* prospective, *Retro* retrospective, *LCS* low contact stress, *WMT* Wright Medical Technology, *mo* month(s), *yrs* years

*Stratification into First and Second Generation BCR TKA is not standardized. In comparison to the novel TKA designs (Vanguard XP and Journey II XR), prosthesis available previously were classified as first generation. This cannot take all developmental steps and evolutions of BCR TKA into account

§Only patients with KSS function score of > 30 and pre-operative valgus > 5° were included

$Patient-specific instruments by Zimmer Biomet indicate use of Vanguard™ XP/CR

#Study by Pelt [31] includes the subset of BCR cases of Alnachoukati [2]

^Cases with surgical complications were excluded from the study; two studies with same cohorts but different analysis; study by Peng and Arauz report the same cohort/FU/KSS scores, etc.

Table 2 Indications for BCR TKA

Author*	Year	Indications			
		Etiology	Deformity	Contracture	Soft tissue
First generation					
Buechel [8]	1990		+		
Cloutier [13]	1991	OA; RA; ON	Valgus < 30° Varus < 30°		
Cloutier [14]	2001	OA; RA	Valgus 11°–20° Varus 1°–30°	25°–65°	
Lavoie [26]	2018	+ (no limitations)	+ (Indirect)	+	
Pritchett [35]	1996		+ (No severe deformity)		
Pritchett [38]	2004		Valgus > 15° Varus > 20°	> 20°	
Pritchett [37]	2013				
Pritchett [36]	2015	OA; RA; ON	Valgus < 15° Varus < 15°		
Sabouret [40]	2013	OA; RA			
Stiehl [42]	2006	OA; RA; PT; OT			
Second generation					
Alnachoukati [2]	2018	+			+
Baumann [5]	2017	+	Valgus < 10° Varus < 10°		
Christensen [11]	2017	+	+ (Minimal deformity)	+	
Pelt [31]	2019	OA; RA; revision	Valgus < 15° Varus < 15°	< 15°	
Tsai [45]	2019	Varus OA			

OA osteoarthritis, *RA* rheumatoid (inflammatory) arthritis, *ON* osteonecrosis, *PT* post-traumatic, *OT* other
"+" indicates mentioning of indications without specification

Table 3 ACL status before BCR TKA

Author*	Year	ACL status		Imaging
		Macroscopic	Clinical function (test)	
First generation				
Cloutier [13]	1991	+		
Cloutier [14]	2001	+	Intra-operative: anterior drawer test	
Jenny [20]	1998	+		
Lavoie [26]	2018		Pre-operative: anterior drawer test	
Pritchett [38]	2004	+	+	
Pritchett [37]	2013			
Pritchett [36]	2015	+	Lachmann test, pivot shift test, anterior drawer test	
Sabouret [40]	2013	+	Lachmann test, anterior drawer test	
Second generation				
Alnachoukati [2]	2018	+		
Baumann [5]	2017		+	
Christensen [11]	2017	+	+	
Kalaai [21]	2019		Lachmann test and anterior drawer test	
Kono [24, 25]	2019			MRI
Pelt [31]	2019	+	Lachmann test and anterior + posterior drawer test	X-ray
Tsai [45]	2019		Lachmann test nd anterior + posterior drawer test	

"+" indicates mentioning of status/test

Table 4 Clinical outcomes of BCR TKA

Author*	Year	Clinical results				UCLA	FJS	WOMAC	PROMIS PF CAT (SD; range)	KOOS
		Pre-OP KSS	Post-OP KSS (SD or range)	Pre OP ROM (Flexion) (°)	Post OP ROM (Flexion) (°)					
First generation										
Cloutier [13]	1991	39 (HSS)	81 (HSS)	85 (5–135)	110 (n.a.)					
Cloutier [14]	2001	33 (0–40) Knee 44 (0–62) Function	91 (9)		107 (13)					
Jenny [20]	1998	50 (12) Knee 41 (20) Function	89 (11) Knee 80 (13) Function	106 (13)	102 (16)					
Lavoie [26]	2018	49 (n.a.) Knee 57 (n.a.) Function	84 (n.a.) Knee 75 (n.a.) Function	127 (100–160)	118 (80–150)					
Moro-oka [27]	2007		87 (85–89)		129 (120–135)					
Pritchett [35]	1996		92 (85–100)		119 (98–141)					
Pritchett [38]	2004	39 (n.a.) Knee 42 (n.a.) Function	93 (n.a.) Knee 77 (n.a.) Function		119 (n.a.)					
Pritchett [37]	2013		93 (n.a.) Knee 77 (n.a.) Function		119 (n.a.)					
Pritchett [36]	2015	42 (26–49)	91 (61–100)	104 (10–130)	117 (90–130)					
Sabouret [40]	2013	33 (0 to 40) Knee 44 (0 to 62) Function	87 (27–100) Knee 68 (0–100) Function	104 (10–130)	103 (80–120)					
Second generation										
Alnachoukati [2]	2018	48 (20) Total 58 (18) Function	89 (14) Function 96 (6) Total	116 (14)	121 (9)	6 (1)				
Arauz [3] and Peng [32]	2019	58.1 (11.8) Total	87.9 (16.7) Total							
Baumann [5]	2017			120.3 (12.6)	116 (13)		53.4 (26.4)			
Christensen [11]	2017				122 (8)					
Hennessy [19]	2019	58.1 (11.8) Total	86.6 (16.7) Total							
Kalaai [21]	2019	36.2 (8.1) OKS	22.0 (10.1) OKS				58.4 (33.7)	81.0 (20.3)		
Kono [24, 25]#	2019		20.9 (3.3) Symptoms 30.8 (7.4) Satisfaction 10.3 (2.2) Expectation 78.6 (17.3) Function*	3.2 (2.2) Ex 128.7 (6.1) Flex	4.1 (4.4) Ex 117.9 (13.1) Flex					81.9 (8.5) Pain 79.2 (10.1) Symptoms 80.8 (10.0) Fu d living 49.1 (23.8) Fu Sport 66.9 (17.3) QoL
Pelt [31]	2019			121	123				45 (8; 23–63)	
Tsai [45]	2019	58.5 (11.8) Total	86.6 (16.7) Total							

KSS Knee Society Score, *ROM* range of motion, *OKS* Oxford Knee Score, *FJS* Forgotten Joint Score, *UCLA* University of Los Angeles score, *PF CAT* physical function computer adaptive test

+Pritchett: Publications on similar cohort. Results identical

^Cases with surgical complications were excluded from the study

*Only patients with > 30 points were included

#Kono published two studies with the same cohort; WOMAC [25] and KSS [24]

Notably, this does not indicate similarity between the different designs of BCR TKA in either group.

In this literature review, no randomized controlled trials comparing BCR TKA to other non-ACL sparing knee systems were identified. The majority of studies were retrospective in design ($n = 8$) or the design was not mentioned ($n = 7$). Additionally, multiple cohort studies compared groups either prospectively or retrospectively. Because this review did not aim to compare BCR TKA to other implants, the lack of high quality comparative studies was acceptable.

Overall, the published information regarding indications for BCR TKA was imprecise. While most authors mentioned restrictions to indications, many were vague regarding the exact specifications and limits. The underlying diagnosis was mostly osteoarthritis (OA) but inflammatory arthritis did not lead to exclusion in at least five studies [13, 14, 36, 40, 42]. This is of particular interest because inflammatory arthritis often impacts the ACL. Interestingly, Cloutier reported good results in patients with a partially degraded ACL [13, 14]. However, no correlation with the diagnosis was reported. More research is required to improve the understanding of inflammatory arthritis and ACL preservation arthroplasty. Additionally, the extent and degree of OA may be relevant factors for outcome. Baumann et al. limited indications to bi-compartmental OA, while Sabouret et al. and Christensen et al. included bi- and tri-compartmental OA [5, 6, 11, 40]. This demonstrates the wide spectrum of potential indications. The current literature does not provide sufficient information to support specific indications. Of note, there is considerable debate regarding the influence of preoperative deformity for indications of different TKA designs. The coronal alignment plays a significant role in planning and soft tissue management. Therefore, the range of acceptable deformity in more tissue-sparing BCR TKA is still unclear. It was noted, that the authors of publications on second generation implants showed a more restrictive range of indications. In particular, the acceptable degree of deformities was lower in most studies. Overall, the literature was not able to show a clear limitation for indications. Nonetheless, a certain tendency toward minor deformity in BCR TKA was observed. Similar observations were made for preoperative flexion contractures. Indication limitations may be applied due to a more rigorous patient selection during learning and in research projects.

A functional intact ACL is a precondition for a BCR TKA. Macroscopic degeneration might still be acceptable and not impair functional outcomes [13, 14]. In this review, not all authors reported on an examination of the ACL prior to or during surgery. However, at a minimum most mentioned macroscopic inspection during surgery [2, 11, 13, 14, 20, 31, 36, 38, 40]. Additionally, most authors performed clinical functioning tests [11, 13, 14, 21, 26, 31, 36, 38, 40, 45]. Thus, it can be derived that a function test before surgery is recommended and intraoperative assessment will further guide toward appropriateness of patients for BCR TKA. Publications discussing the role of MRI imaging or conventional radiological signs as an indicator of ACL insufficiency were limited [24, 25, 31]. Future studies should focus on the role of ACL examinations to select optimal candidates for surgery.

Clinical outcomes scores for BCR TKA were collected and presented in Table 4. KSS scores were widely within expected ranges of traditional TKA. Patient reported preference of knees after uni- or bi-lateral joint replacement is an additional means to assess the overall patient reported function of an arthroplasty. Preference for BCR TKA over other TKA implants was first reported by Pritchett [38, 39]. These reports were consistent over long follow-up periods. Notably, Baumann et al. compared BCR TKA patients with posterior stabilized (PS) TKA systems and UKA. In the BCR TKA group, 13 (65%) perceived a more stable feeling in the TKA knee compared to the contralateral side contrasting 8 (40%) and 10 (50%) in the UKA and PS TKA groups, respectively. UKA as well as BCR TKA showed superior sway with closed eyes over PS TKA. Overall, Baumann et al. found proprioceptive function of BCR TKA to be comparable to UKA [5]. In contrast, the knee scores showed overall good ratings for the objective part, but less for the patient-reported function part. Baumann et al. and Kalaai et al. reported Forgotten Joint Scores [5, 21]. They were comparable between BCR TKA and UKA with significant improvement over TKA at a follow-up of 18 months. However, no randomization was performed and wide ranges were reported. Of note, the used implant has been recently shown to have high early revision rates [11, 31]. Revisions may be attributed to learning curves and a potentially more demanding surgical technique [31]. Yet, Pelt et al. were not able to show these effects for their cohort with a second generation implant [31].

Revisions and/or survival of BCR TKA were reported in 13 studies. Cloutier et al. reported a survivorship rate of 95% after 10 years and 82% after 22 years for a first generation design [14, 40]. However, 38% of patients had limited range of motion (ROM) and pain. The authors attribute this high number to an elevated ligamentous tension [13, 14]. Despite technical advances, a higher proportion of patients have reduced ROM compared to standard implants. This may be related to the surgical technique and more complex balancing of the soft tissues including ACL and PCL during BCR TKA, but no specific mode of failure analysis was reported in this regard. Christensen recently found a higher rate of early revisions in BCR TKA compared to PCL-retaining implants [11]. A thorough analysis by Pelt et al. found revision rates of 13.5% after 3 years. Even in a worst-case scenario where all lost to follow-up cases were also revised, the survival rate was calculated to be only 71%. The largest

Table 5 Survival and revision rates of BCR TKA

Author*	Year	Survival		
		Revisions % (*n*)	Kaplan Meyer survival % (confidence interval)	Follow-up Mean (range)
First generation				
Buechel [8]	1990	0% (0)^{CL}	100%^{CL}	6 yrs ^{CL}
		2.2% (1)^{C}	90.91% ^{C}	12 yrs ^{C}
Cloutier [13]	1991	3.5% (1)		10–13 yrs
Cloutier [14]	2001	4.3% (7)	95% (93–97%)	10 (9–11) yrs
Jenny [20]	1998	6.3% (2)		2–3 yrs
Lavoie [26]	2018	1% (1)		18 (5–50) mo vs 38 (13–71) mo
Pritchett [36]	2015	4.5% (22)	89% (82–93%)	23 (20–24) yrs
Sabouret [40]	2013	17.8 (29)	82% (76–88%) any reason	22 yrs
Second generation				
Alnachoukati [2]	2018	1.4% (2)*		12 (1–33) mo
Baumann [5]	2017	5% (1)		8.5 (6–12) mo
Baumann [6]	2018	5.9% (2)		18 mo
Christensen [11]	2017	10.6% (7)		18 (2–32) mo
Kalaai [21]	2019	1.6% (1)	98.4%§	36 mo
Pelt [31]	2019	13.5% (19)	88% (82–93%)	3 yrs
		17% (41)$^{\$}$	71% (64–77%)$^{\$}$	

CL cementless, *C* cemented, *mo* months, *yrs* years

*9 knees (6.2%) suffered from intraoperative tibial island fracture with screw-refixation during the learning phase

§Calculated as 100% minus revisions. One patient died of unrelated issues between 24 and 36 months FU; not represented in survival analysis

$Implant-revisions (13.5%) and any revision (17%) for followed patients ($n = 141$) reported; worst case KM survival includes lost to FU cases; no learning curve effects detected

series of BCR TKA patients with long-term survivorship was presented by Pritchett et al. [36] The Kaplan–Meier survivorship rate was 89% (95% CI 82–93) with revision for any reason as an endpoint. The main reason for revision was polyethylene (PE) wear of a non-cross-linked PE. Excluding these revisions, the 20-year survivorship rate rises to 96%. Additionally, in one modern XR design, tibial component loosening posed a potential issue [31]. Here, newer implants with asymmetrical inlays may show improved survival [24].

Kinematic analysis showed heterogeneous results for BCR TKA regarding functional reconstruction of the native kinematics. Arauz et al. found an incomplete "screw-home" mechanism and high variability in pivot patterns [3]. Arauz as well as Kono et al. reported that the articular surface of BCR TKA might play a significant role in insufficient reconstruction of normal knee function [3, 24, 25]. The novel introduction of BCR TKA with asymmetrical convex lateral inlays may improve the kinematic function of BCR TKA [24, 25, 46].

Further studies are needed to investigate mid- to long-term survivorship for the second generation of BCR implants with highly cross-linked PE and asymmetrical inlays.

There are limitations to this review. First, while there were no randomized controlled trials available for inclusion, there were several prospective cohort studies. For second generations of BCR TKA, study designs that collect data on survival/revisions as well as patient-reported outcomes should be employed. Secondly, the review combined old and new BCR TKA designs that were stratified into first and second generations. While first generation designs are not available anymore, it is of importance to understand the clinical results of these early designs for interpretation of the current technology. The comparability of BCR TKA designs is further limited due to the complexity of the various design aspects. However, this review aimed to provide insights into the overall group of BCR TKA designs and thus was not limited to additional specific design aspects. Finally, the available data were not sufficient to guide surgeons regarding indications for BCR TKA and further research is needed.

In conclusion, there is a wide variety of BCR TKA systems and very limited data on indications for these arthroplasty systems. First generation designs showed good long-term survival with good clinical outcomes. For second generation designs, heterogeneous results regarding survival and outcomes in the short to midterm follow-up were reported. Further prospective randomized trials may be necessary to investigate long-term survivorship and limitations to determine the ideal patient for BCR TKA and provide adequate guidance on indications and their limitations.

Author contributions SE carried out the pilot search strategy and screened the titles and abstracts. Full text retrieval and analysis were carried out by CKB. CKB and DDF conceived and drafted the manuscript. CR advised on the review design and helped to draft the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest CKB and SE are employees of Smith and Nephew. DDF was employee of Smith and Nephew during creation of the work. Employees of Smith and Nephew may own or be eligible to stock and stock options of Smith and Nephew. CR did not report any conflicts of interest.

Appendix

Arthroplasty systems and manufacturers based on the identified literature:

First generation:

Genesis™ II (Smith + Nephew, Memphis, TN, USA).

Hermes™ 2C ACR (Ceraver-Osteal, Roissy, France).

LCS™ BCR, CR, PS & Rotating (DePuy, Warsaw, IN, USA).

MLP (Wright Medical Technology, Memphis, TN, USA).

N2C™ & Natural-Knee™ (Zimmer GmbH, Winterthur, Switzerland)

Oxford™ UKA (Biomet, Warsaw, IN, USA).

Search™ BCR TKA (Aesculap, Tuttlingen, Germany).

Townley Anatomic™ & Biopro™ (Biopro, Port Huron, MI, USA).

Second Generation:

Journey™ II XR (Smith + Nephew, Memphis, TN, USA).

Vanguard™ XP & CR (Biomet, Warsaw, IN, USA).

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