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Research article

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Periacetabular osteotomy with intraoperative computer-assisted modalities: a systematic review

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ABSTRACT

The role of intraoperative computer-assisted modalities for periacetabular osteotomy (PAO), as well as the perioperative and post-operative outcomes for these techniques, remains poorly defined. The purpose of this systematic review was to evaluate the techniques and outcomes of intraoperative computer-assisted modalities for PAO. Three databases (PubMed, CINAHL/EBSCOHost and Cochrane) were searched for clinical studies reporting on computer-assisted modalities for PAO. Exclusion criteria included small case series (<10 patients), non-English language and studies that did not provide a description of the computer-assisted technique. Data extraction included computer-assisted modalities utilized, surgical techniques, demographics, radiographic findings, perioperative outcomes, patient-reported outcomes (PROs), complications and subsequent surgeries. Nine studies met the inclusion criteria, consisting of 208 patients with average ages ranging from 26 to 38 years. Intraoperative navigation was utilized in seven studies, patient-specific guides in one study and both modalities in one study. Three studies reported significantly less intraoperative radiation exposure ($P < 0.01$) in computer-assisted versus conventional PAOs. Similar surgical times and estimated blood loss ($P > 0.05$) were commonly observed between the computer-assisted and conventional groups. The average post-operative lateral center edge angles in patients undergoing computer-assisted PAOs ranged from 27.8° to 37.4°, with six studies reporting similar values ($P > 0.05$) compared to conventional PAOs. Improved PROs were observed in all six studies that reported preoperative and post-operative values of patients undergoing computer-assisted PAOs. Computer-assisted modalities for PAO include navigated tracking of the free acetabular fragment and surgical instruments, as well as patient-specific cutting guides and rotating templates. Compared to conventional techniques, decreased intraoperative radiation exposure and similar operative lengths were observed with computer-assisted PAOs, although these results should be interpreted with caution due to heterogeneous operative techniques and surgical settings.

INTRODUCTION

Periacetabular osteotomy (PAO) can be performed to treat symptomatic hip instability in the setting of acetabular undercoverage [1]. Good long-term results following PAO have been demonstrated with appropriate patient selection [2]. However, the surgical technique is technically demanding with a steep learning curve that is susceptible to complications [3–5]. Challenging aspects of PAO surgery include performing osteotomies in the correct trajectory with limited visualization and reducing the free acetabular fragment to provide adequate femoral head coverage without impingement [6, 7]. While an accurate correction of the free acetabular fragment has been associated with improved post-operative outcomes, achieving this targeted zone of correction can be challenging even among experienced hip surgeons [8, 9].

Computer-assisted modalities have been proposed as a resource to facilitate PAO surgery [10–13]. Advanced computer technologies have been employed in hip and shoulder arthroplasties for intraoperative navigation and patient-specific guides, respectively [14, 15]. However, the current applications for intraoperative computer assistance for PAO remain unclear, including the specific aspects of the surgery that these modalities are attempting to improve. Proposed benefits of intraoperative computer-assisted modalities include decreased radiation exposure and increased accuracy of the free acetabular fragment correction [6, 16]. However, potential disadvantages include increased surgical costs and longer operative times to utilize the technology.

The purpose of this review is to evaluate intraoperative computer-assisted modalities for periacetabular osteotomy (PAO) to (i) provide a qualitative description of the current applications for this technology, (ii) analyze perioperative outcomes [e.g. surgical time, estimated blood loss (EBL) and radiation exposure] and (iii) assess post-operative radiographic

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and patient-reported outcomes (PROs). It was hypothesized that computer-assisted modalities would (i) include navigation of the free acetabular fragment and patient-specific guides, (ii) decrease surgical time, EBL and radiation exposure and (iii) demonstrate improved radiographic outcomes and PROs.

METHODS

Literature search

A systematic review was performed in compliance with the Preferred Reporting for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [17]. In June 2022, the PubMed, CINAHL/EBSCOHost and Cochrane databases were searched for the keywords: '((periacetabular osteotomy) OR (Bernese osteotomy)) AND ((planning) OR (navigation) OR (computer assisted) OR (image guided) OR (augmented reality) OR (templating) OR (guidance system) OR (machine learning) OR (cutting guide) OR (template)).' The articles selected for review were evaluated by two authors (A.J.C. and A.E.J.). The full-text studies that were assessed also underwent review of their bibliographies to evaluate for additional applicable articles that were not obtained in the initial database search. Institutional Review Board (IRB) approval was not necessary for this study as it did not include protected patient information.

Study criteria

Criteria for inclusion in this review included clinical studies utilizing intraoperative computer-assisted modalities during PAO. Computer-assisted modalities were defined as navigation in real time or at a single time point, as well as patient-specific instrumentation, templates or cutting guides that were affixed to the patient intraoperatively. Exclusion criteria were case reports, case series of <10 patients, non-English language studies, studies that include pelvic osteotomies other than Bernese PAO or spherical acetabular osteotomies to treat dysplasia and studies that did not provide a description of the computer-assisted technique. Additionally, studies were excluded if they included computer-assistance 'only' in the preoperative phase (without a concomitant intraoperative modality), such as preoperative planning software or bone models. Furthermore, studies that duplicated a prior cohort were excluded so that each patient cohort was only reported once in this review. Disagreements involving the included studies were resolved by discussion from two of the authors (A.J.C. and A.E.J.).

Quality assessment

The methodological quality of the included studies was graded with the Methodological Index of Non-Randomized Studies (MINORS) criteria [18]. Two reviewers (A.J.C. and A.E.J.) separately evaluated each study, and disagreements were resolved by discussion. The interobserver agreement between authors was calculated.

Data collection

Data extraction of the studies included title, author, year, journal, institution, level of evidence (LOE), study design, dates of study period, surgical approach, osteotomy technique and fixation methods. Computer-assisted modalities were assessed for

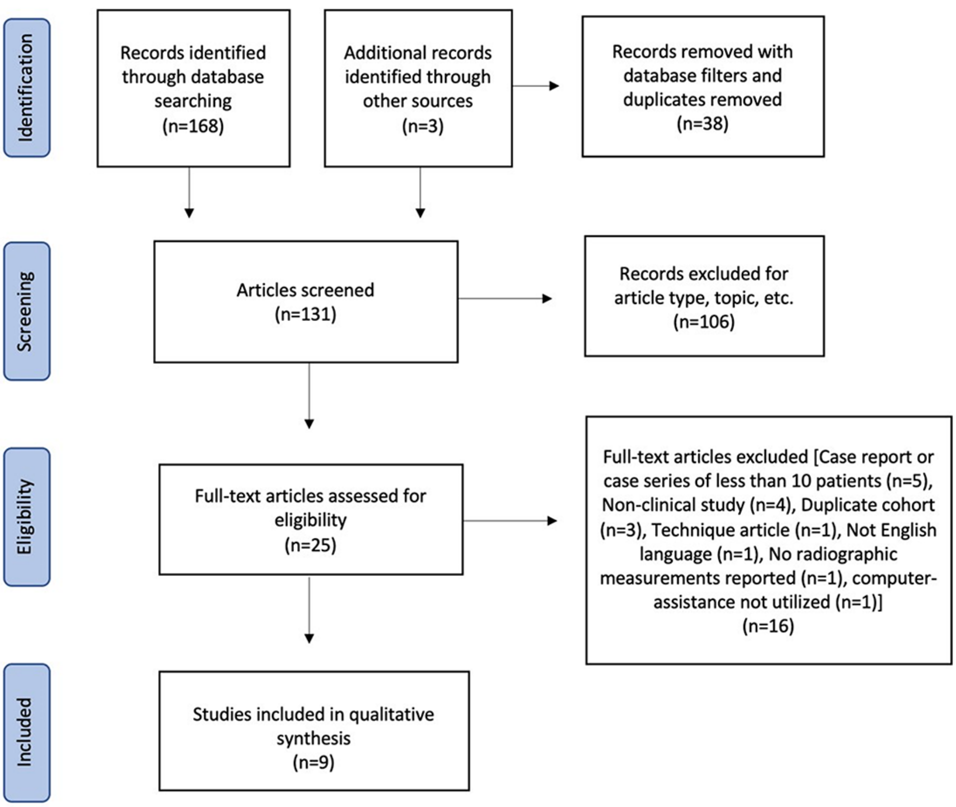

Fig. 1. PRISMA flowchart of literature search.

characteristics of intraoperative navigation and patient-specific guides, as well as preoperative planning methods. Data were also collected for patient demographics, preoperative and post-operative radiographic findings, perioperative outcomes (e.g. operative time, EBL and radiation exposure), PROs, complications and subsequent surgeries. For studies that reported a mean and standard deviation, forest plots were generated for operative time, EBL and post-operative lateral center edge angles (LCEAs).

RESULTS

Study characteristics

The initial search yielded 168 articles, along with another three articles identified through a bibliography search (Fig. 1). After duplicates were removed and screening of content, 25 full-text articles were reviewed. Sixteen of these studies were excluded for additional reasons, leaving nine articles [12, 16, 19–25] for qualitative analysis in this systematic review.

Two studies [12, 19] were published before 2007, and the remaining studies were dated after 2015 (Table I). There was one Level II, six Level III and two Level IV studies. Six studies included a comparative group of conventional PAO surgery without computer assistance [16, 19, 22–25]. The average MINORS score was 13. Commonly observed methodological domains of weakness include lack of blinded assessment of outcomes, failure to prospectively calculate sample size and loss to follow-up >5%. The interobserver agreement of the two MINORS graders was 89%.

Surgical technique

Four studies [12, 20, 23, 25] performed a Bernese PAO [1] through an anterior approach, whereas another four studies [16, 19, 21, 24] utilized a spherical PAO via a trans-trochanteric approach (Table II). Three studies [16, 21, 22] reported fixation with bioabsorbable screws, while the remaining studies used metal screws or did not specify fixation.

Patient characteristics

The nine studies included 208 hips undergoing computer-assisted PAO, with an average age ranging from 26 to 38 years. One study [22] noted that 87.3% of the patients were men, while the remaining studies were comprised predominantly of female patients. The mean body mass index (BMI) that was reported had a range of 21 to 25 kg/m^2.

Various preoperative radiographic measurements for patients undergoing computer-assisted PAO were observed across all included studies (Table III). Seven studies [16, 19–23, 25] reported mean preoperative LCEAs which ranged from 0° to 20.5°. Five studies [12, 16, 20, 21, 25] described average Tönnis angles in their cohorts that ranged from 15.1° to 25.3°.

Table I. *Study characteristics*

Author	*Year*	*Journal*	*Institution*	*LOE*	*Study design*	*Average MINORS score*	*Dates of study*
Hayashi *et al.*	2018	International Orthopedics	Kobe Kaisei Hospital (Kobe, Japan)	III	Comparative cohort	14.5	2014 to 2016
Hseih *et al.*	2006	Acta Orthopaedica	Chang Gung Memorial Hospital (Taoyuan, Taiwan)	II	Comparative cohort	18.5	2002 to 2003
Imai *et al.*	2020	International Orthopedics	Ehime University Graduate School of Medicine (Ehime, Japan)	III	Comparative cohort	14	2007 to 2013
Inaba *et al.*	2016	Clinics in Orthopedic Surgery	Yokohama City University (Yokohama, Japan)	III	Comparative cohort	13	2011
Langlotz *et al.*	1997	Computer Aided Surgery	University of Bern (Bern, Switzerland)	IV	Case series	3	1995
Mihalic *et al.*	2021	International Orthopedics	Valdoltra Orthopaedic Hospital (Ankaran, Slovenia)	III	Comparative Cohort	16.5	2013 to 2019
Murphy *et al.*	2016	Journal of Orthopaedic Surgery and Research	Orton Orthopaedic Hospital (Helsinki, Finland) and Johns Hopkins University (Baltimore, USA)	IV	Case series	9	2005 to 2009
Takao *et al.*	2017	International Journal of Computer Assisted Radiology and Surgery	Osaka University Graduate School of Medicine (Osaka, Japan)	III	Comparative cohort	10.5	2011 to 2014
Wang *et al.*	2019	Journal of Orthopaedic Surgery and Research	The First Affiliated Hospital of Bengbu Medical College (Anhui, China)	III	Comparative cohort	19	2017

Table II. ***Surgical techniques and demographics***

Author	*Preoperative planning*	*Navigation*	*Patient-specific guide*	*Type of osteotomy*	*Fixation*	*Age (years)*	*Female (%)*	*Patient composition*
Hayashi *et al.*	Osteotomy lines and planned correction	Probe (to assess acetabular correction)	N/A	Spherical PAO (anterior)	Two or three poly-lactic acid screws or metal cancellous screws	Computer-assisted: 31.5 ± 11.2 Conventional: 29.1 ± 11.9	Total: 12.7%	Not reported
Hseih *et al.*	None	Osteotomes	N/A	Spherical PAO (trans-trochanteric)	Three or four 3.5-mm cortical screws	Computer-assisted: 34 ± 7.3 Conventional: 36 ± 5.7	Computer-assisted: 94% Conventional: 88.8%	Computer-assisted, body weight (kg): 52 ± 6.7 (range, 45–85) Conventional, body weight (kg): 54 ± 7.9 (range, 48–80)
Imai *et al.*	Osteotomy lines and planned correction	Probe (to assess acetabular correction)	N/A	Spherical PAO (trans-trochanteric)	Four to five hydroxyapatite screws	Computer-assisted: 37.7 ± 1.4 (range, 15 to 52) Conventional: 41.1 ± 1.5 (range, 22 to 56)	Computer-assisted: 86.2% Conventional: 82.5%	Computer-assisted, BMI (kg/m^2): 23.5 ± 0.5 (range, 17.7–37.8) Conventional, BMI (kg/m^2): 23.0 ± 0.6 (range, 16.7–32.2)
Inaba *et al.*	Osteotomy lines and planned correction	Probe (to assess acetabular correction), drill, and osteotomes	N/A	Spherical PAO (trans-trochanteric)	Three 4.5 mm polylactic acid absorbable screws	Not reported	Computer-assisted: 90.9% Conventional: 95.0%	Not reported
Langlotz *et al.*	None	Osteotomes	N/A	Bernese PAO (anterior)	Not specified	Computer-assisted: 33.5 (range, 19 to 47)	Computer-assisted: 75%	Not reported
Mihalic *et al.*	Osteotomy lines and planned correction	Acetabular fragment (real-time), osteotomes	Biocomposite plastic cutting guide (supra-acetabular and retro-acetabular osteotomies)	Bernese PAO (anterior)	Three 4.5 mm metal screws	Computer-assisted: 33.6 ± 10.8 Conventional: 36 ± 13.5	Total: 82.8%	Computer-assisted, BMI (kg/m^2): 24.7 ± 3.8 Conventional, BMI (kg/m^2): 22.7 ± 2.9

(continued)

Table II. (Continued)

Author	*Preoperative planning*	*Navigation*	*Patient-specific guide*	*Type of osteotomy*	*Fixation*	*Age (years)*	*Female (%)*	*Patient composition*
Murphy *et al.*	Osteotomy lines and planned correction	Acetabular fragment (single-time point)	N/A	Bernese PAO (anterior)	Screws (unspecified type or quantity)	Computer-assisted: 34 years (range, 22 to 48)	Computer-assisted: 72.7%	Computer-assisted, body weight (kg): 59 (range, 25–87)
Takao *et al.*	Osteotomy lines and planned correction	Probe (to assess acetabular correction) and osteotomes	N/A	Spherical PAO (trans-trochanteric)	Three to four bioabsorbable screws	Total group: 33.7 ± 9.1 (range, 15 to 48)	100%	Body weight (kg) 54.7 ± 19.1 (range, 33.7–77.0); height (cm): 156.7 ± 8.3 (range, 127–170)
Wang *et al.*	Osteotomy lines and planned correction	N/A	Plastic cutting guide (supra-acetabular, retro-acetabular, ischial, and pubic osteotomies). Plastic rotating template (to guide acetabular correction)	Bernese PAO (anterior)	Three cortical screws	Computer-assisted: 26 ± 8 (range, 16 to 38) Conventional: 25 ± 5 (range, 18 to 35)	Computer-assisted: 62.5% Conventional: 58.3%	Computer-assisted, BMI (kg/m^2): 21 ± 2 (range, 19–23) Conventional, BMI (kg/m^2): 22 ± 2 (range, 18–24)

Data are presented as means ± SD (range, lower limit to upper limit) or *n* (%) unless otherwise noted. All angles are reported as degrees. N/A, Not applicable.

Table III. ***Radiographic and perioperative information***

Author	*Group*	*Preoperative radiographic findings*	*Post-operative radiographic findings*	*Length of surgery (min)*	*EBL (mL)*	*Radiation exposure*
Hayashi *et al.*	Computer-assisted ($n = 30$)	LCEA: 12.6 ± 8.1 ACEA: 43.9 ± 12.9 AHI (%): 68.2 ± 12.5	LCEA: 30.8 ± 5.1 ACEA: 62.1 ± 9.7 AHI (%): 80.2 ± 8.0	117 ± 18	463 ± 109	Not reported
	Conventional ($n = 23$)	LCEA: 13.6 ± 7.4 ACEA: 42.7 ± 15.8 AHI (%): 68.8 ± 5.9	LCEA: 29.9 ± 5.2 ACEA: 67.7 ± 9.7 AHI (%): 82.6 ± 7.6	114 ± 19	475 ± 206	
Hseih *et al.*	Computer-assisted ($n = 18$)	LCEA: 0 (range, −7 to 15) Sharp angle: 60 (range, 55 to 68) AHI (%): 55 (range, 35 to 65) ACEA: −2 (range, −10 to 10)	LCEA: 32 (range, 25 to 40) Sharp angle: 43 (range, 39 to 48) AHI (%): 95 (range, 85 to 100) ACEA: 34 (range, 29 to 40)	Not reported	Not reported	0.6 ± 0.5 intraoperative radiographs (range, 0 to 2)
	Conventional ($n = 18$)	LCEA: 2 (range, −15 to 10) Sharp angle: 58 (range, 50 to 69) AHI (%): 52 (range, 38 to 60) ACEA: 3 (range, −15 to 13)	LCEA: 35 (range, 28 to 40) Sharp angle: 60 (range, 55 to 68) AHI (%): 92 (range, 85 to 100) ACEA: 29 (range, 25 to 35)			4.4 ± 1.6 intraoperative radiographs (range, 2 to 7)
Imai *et al.*	Computer-assisted ($n = 58$)	Tönnis Grade 0: 17; Grade 1: 37; Grade 2: 4; Grade 3: 0	LCEA: 37.4 ± 0.9 (range, 25 to 50)	Not reported	Not reported	Not reported
	Conventional ($n = 40$)	Tönnis Grade 0: 10; Grade 1: 23; Grade 2: 7; Grade 3: 0	LCEA: 34.5 ± 1.1 (range, 23 to 49) ACEA: 36.5 ± 2.1 (range, 0 to 70) Sharp angle: 36.8 ± 0.6 (range, 27 to 44) AHI (%): 82.7 ± 1.0 (range, 71 to 95)			
Inaba *et al.*	Computer-assisted ($n = 23$)	Not reported	LCEA: 27.8 ± 10.7 AI: 5.0 ± 8.1 Sharp angle: 41.6 ± 5.7 AHI (%): 81.0 ± 11.9	142 ± 34	589 ± 377	5 ± 10 seconds (fluoroscopy time)
	Conventional ($n = 23$)		LCEA: 29.3 ± 8.8 AI: 5.3 ± 6.3 Sharp angle: 40.2 ± 4.8 AHI (%): 82.0 ± 10.6	107 ± 43	428 ± 281	44 ± 21 seconds (fluoroscopy time)

(continued)

Table III. (Continued)

Author	Group	Preoperative radiographic findings	Post-operative radiographic findings	Length of surgery (min)	EBL (mL)	Radiation exposure
Langlotz *et al.*	Computer-assisted ($n = 12$)	AI: 23.5	AI: 7	200 (range, 150 to 240)	2750 (range, 1200 to 5000)	Not reported
Mihalic *et al.*	Computer-assisted ($n = 30$)	LCEA: 16.7 ± 7.7 AI: 15.1 ± 6.7	LCEA: 31.5 ± 5.9 AI: 3.6 ± 5.9	183 ± 32	652 ± 318	Not reported
	Conventional ($n = 10$)	LCEA: 15.3 ± 7.8 AI: 18.6 ± 5.8	LCEA: 32.1 ± 8.7 AI: 1.4 ± 8.9	203 ± 42	700 ± 306	
Murphy *et al.*	Computer-assisted ($n = 12$)	LCEA: 20.5 (range, −7 to 30) AI: 16.2 (range, 3 to 34)	LCEA: 33.5 (range, 19 to 44) AI: 5.4 (range, −5 to 14)	175 (range, 95 to 210)	Not reported	Not reported
Takao *et al.*	Computer-assisted ($n = 25$)	LCEA: 5.5 ± 8.9 (range, −17 to 18.7) ACEA: 3.7 ± 14.2 (range, −24.6 to 22.8) AI: 22.3 ± 7.7 (range, 6.4 to 38.3) Tönnis Grade 0: 22; Grade 1: 3 Joint congruence—excellent: 21; good: 4; fair or poor: 0 Femoral head displacement (mm): medial 1.2 ± 3.2 (range, −3.8 to 7.8); inferior 2.1 ± 3.1 (range, −2.3 to 9.5) Acetabular fragment thickness 17.5 ± 2.9 mm (range, 11.8 to 23.4)	LCEA: 35.3 ± 6.4 (range, 25.3 to 52.5) ACEA: 36.5 ± 9.5 (range, 18.6 to 57.8)	222 ± 45 (range, 143 to 301)	856 ± 358 (range, 270 to 1640)	Not reported
Wang *et al.*	Computer-assisted ($n = 8$)	LCEA: 10 ± 5 ACEA: 33 ± 7 AASA: 42 ± 4 PASA: 88 ± 3 AAVA: 23 ± 2	LCEA: 31 ± 2 ACEA: 54 ± 2 AASA: 58 ± 2 PASA: 85 ± 3 AAVA: 19 ± 1	102 ± 7 (range, 92 to 110)	695 ± 119 (623 to 833)	4 ± 1 intraoperative radiographs (range, 3 to 6)
	Conventional ($n = 12$)	LCEA: 8 ± 4 ACEA: 32 ± 5 AASA: 42 ± 4 PASA: 88 ±2 AAVA: 22 ± 2	LCEA: 31 ± 3 ACEA: 56 ± 7 AASA: 59 ± 5 PASA: 81 ± 4 AAVA: 20 ± 3	117 ± 19 (range, 93 to 148)	545 ± 81 (415 to 710)	7 ± 2 intraoperative radiographs (range, 5 to 10)

Data are presented as means ± SD (range, lower limit to upper limit) or *n* (%) unless otherwise noted. All angles are reported as degrees. AASA, anterior acetabular sector angle; AAVA, anterior anteversion angle; ACEA, acetabular central edge angle; AHI, Acetabular head index; AI, acetabular index; PASA, posterior acetabular sector angle.

Computer-assisted modalities

Eight studies utilized intraoperative navigation during PAO surgery. The most common form of navigation was tracking of the instruments (e.g. osteotome and drill), which was reported in five studies [12, 16, 19, 21, 25]. Four studies utilized a navigation-tracked probe as a surrogate to help determine the location of the free acetabular fragment after a correction was performed [16, 21, 22, 24]. Two other studies used navigation to track the free acetabular fragment itself, with one system [20] providing this bony orientation at a single time point and another system [25] tracking the bony fragment in real time.

Two studies reported on intraoperative usage of patient-specific guides [23, 25]. One of these guides was a biocomposite plastic cutting guide affixed to the iliac crest with two K-wires, assisting with the supra-acetabular and retro-acetabular osteotomies [25]. Notably, these authors, in addition to this cutting guide, concomitantly utilized a navigation system for real-time tracking of the acetabular fragment and osteotomes. The other study used a plastic cutting guide fixated to the pelvis to aid with all four pelvic osteotomies [23]. Additionally, these authors used a patient-specific rotating template interposed between the pelvis and free acetabular fragment, providing a reference for the correct amount of acetabular reorientation.

In addition to intraoperative navigation and/or patient-specific guides, seven studies utilized computer assistance concomitantly for preoperative planning, which included a template of the osteotomy lines and the planned acetabular correction [16, 20–25]. Notably, the two studies [12, 19] that did not utilize concomitant preoperative planning were published before 2007, while the other seven studies were published after 2015.

Perioperative data

Wang *et al.* [23] reported the shortest mean operative time for the computer-assisted PAO group, utilizing patient-specific cutting and rotating guides 'without' navigation. These authors also noted significantly shorter surgical times for their computer-assisted PAOs compared to conventional PAOs (102 ± 7 min versus 117 ± 19 min, $P < 0.01$). Navigation was used in the remaining six studies [12, 16, 20–22, 25] that reported mean surgical times, which demonstrated higher values that ranged from 117 to 222 min (Fig. 2). Three of these studies [16, 22, 25] compared their computer-assisted PAO cohort versus a conventional PAO group, demonstrating similar operative times ($P > 0.05$).

EBL was reported in six studies [12, 16, 21–23, 25] with average values ranging from 463 to 2750 mL (Fig. 3). Four of these

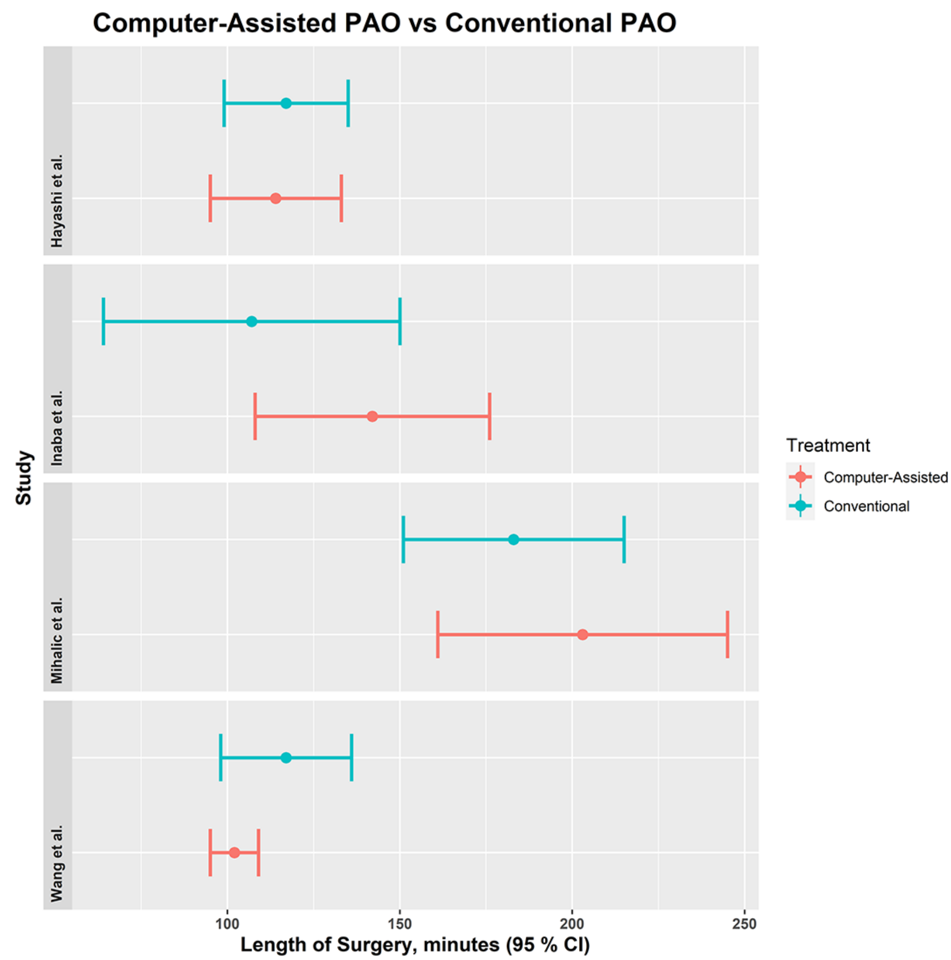

Fig. 2. Graphical depiction of the standardized means for operative time (min), comparing computer-assisted versus conventional PAO.

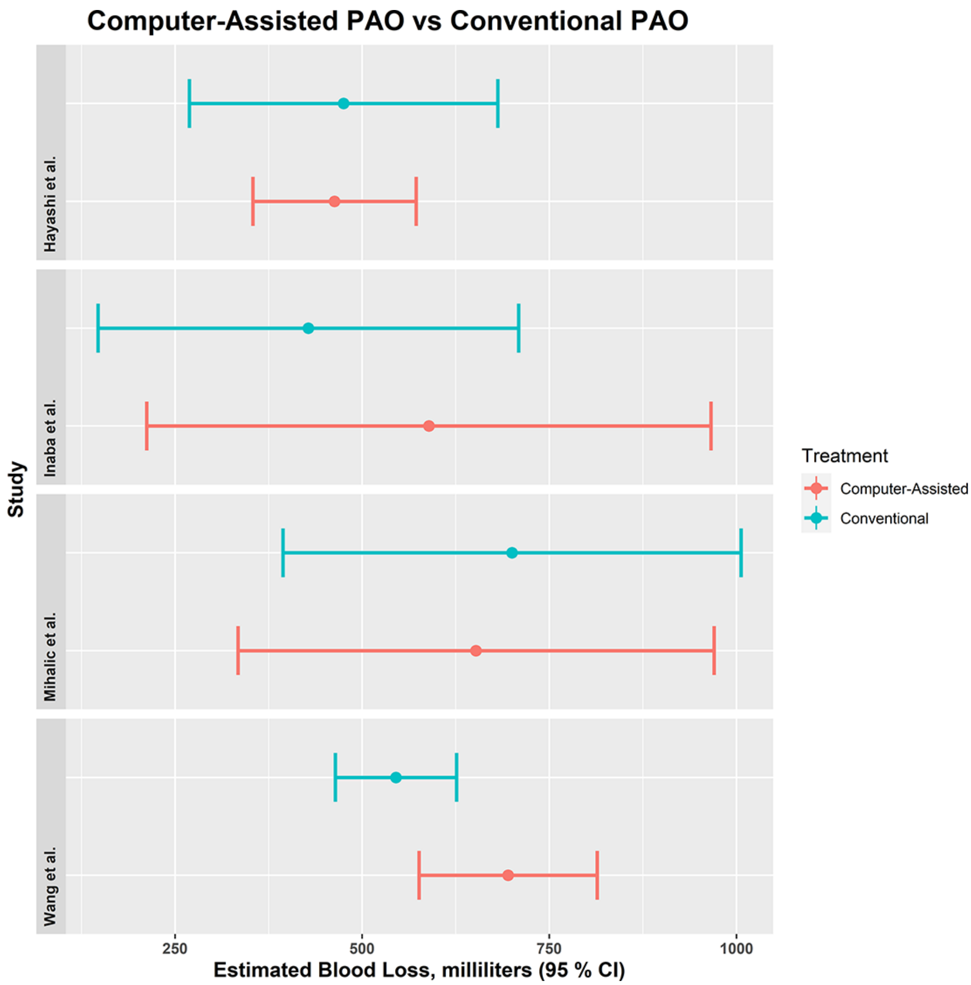

Fig. 3. Graphical depiction of the standardized means for EBL (mL), comparing computer-assisted versus conventional PAO.

studies demonstrated similar EBL ($P > 0.05$) in the computer-assisted cohorts when compared to conventional PAO surgeries [16, 22, 23, 25].

Intraoperative radiation was recorded in three studies [16, 19, 23], which was reported as number of intraoperative radiographs in two studies [19, 23] and fluoroscopy time in another study [16]. All three studies observed significantly less radiation exposure ($P < 0.01$) in the computer-assisted PAOs compared to conventional PAOs (Fig. 4).

Radiographic outcomes and PROs

Eight studies [16, 19–25] reported post-operative LCEAs in patients undergoing computer-assisted PAO, ranging from 27.8° to 37.4° (Fig. 5). Six of these studies [16, 19, 22–25] compared the post-operative LCEAs of the computer-assisted PAO cohort to a conventional PAO group, with all studies demonstrating similar LCEAs between groups ($P > 0.05$). Five studies [12, 16, 20, 21, 25] noted average post-operative Tönnis angles that ranged from −5.2° to 7°.

Six studies [12, 21–25] reported both preoperative and post-operative PROs, with all studies demonstrating an improvement in PROs at most recent follow-up after computer-assisted PAO (Table IV). Notably, the mean follow-up for these studies ranged from 10.8 months to 5 years. Reported in three studies [12, 23, 25], the Harris Hip Score (HHS) was the most commonly utilized PRO, demonstrating an mean preoperative and post-operative values that ranged from 50 to 66 and 77 to 94, respectively. Imai *et al.* [24] and Hayashi *et al.* [22] reported an improvement in Japanese Orthopedic Association (JOA) hip scores from preoperative (74.5 and 76.3, respectively) to post-operative (94.2 and 98.8, respectively).

Complications and subsequent surgeries

Two studies [21, 25] reported complications following computer-assisted PAO, which included five symptomatic hardware removals, one minor heterotopic ossification (Brooker Grade 1–2), one delayed wound closure and one deep infection. Two studies [20, 25] noted subsequent surgeries in patients after computer-assisted PAO, including six symptomatic hardware removals and two conversions to total hip arthroplasty (THA).

DISCUSSION

The main finding of this systematic review was that the intra-operative computer-assisted modalities for PAO reported in the

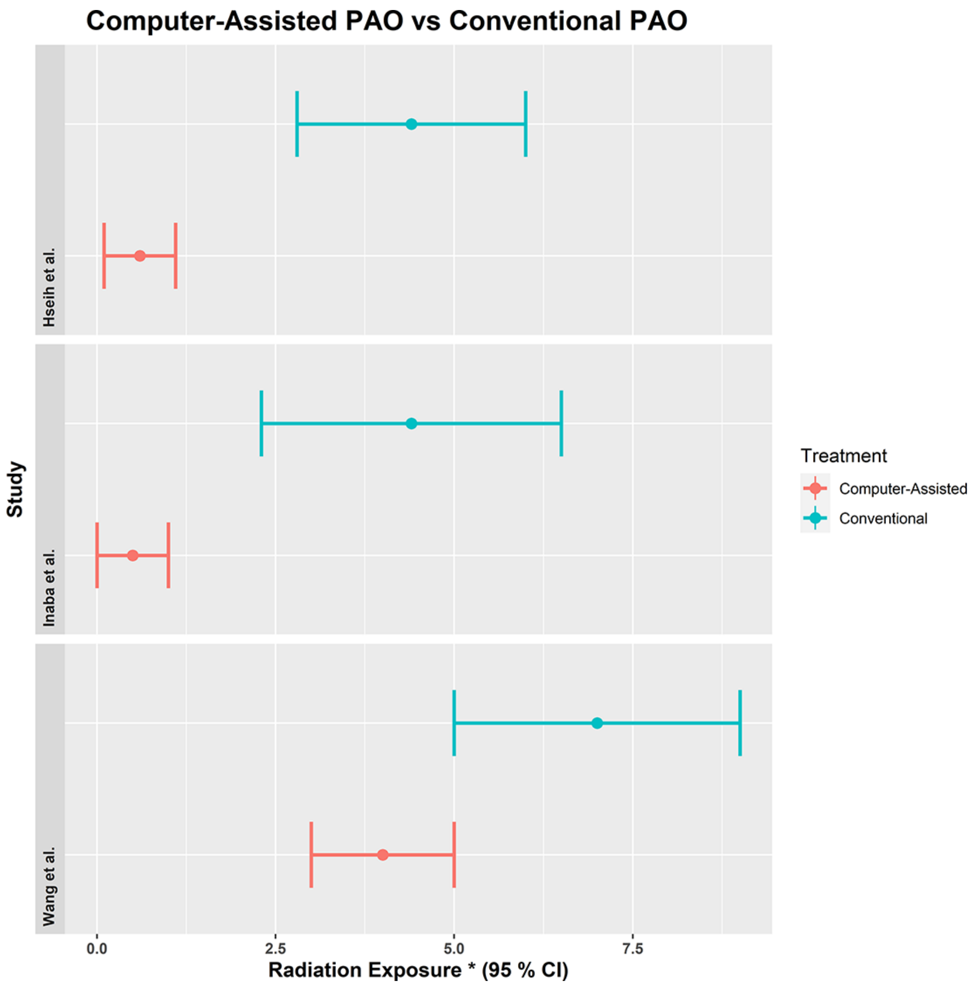

Fig. 4. Graphical depiction of the standardized means for radiation exposure, comparing computer-assisted versus conventional PAO. *Hsieh *et al.* [19] and Wang *et al.* [23] results are reported as number of intraoperative radiographs, and Inaba *et al.* [16] results are reported as 10-s units of fluoroscopy time.

literature included (I) navigated tracking of surgical instruments and the free acetabular fragment and (II) patient-specific cutting guides and acetabular rotating template. These modalities were utilized to facilitate two of the technically challenging aspects of PAO surgery: (I) performing osteotomies in the correct trajectory with limited visualization and (II) reducing the free acetabular fragment to provide adequate femoral head coverage without impingement [6, 7]. The first of these challenges can be assisted by navigated tracking of the surgical instruments or patient-specific cutting guides to ensure that the osteotomies are performed in the appropriate plane. The second challenge can be facilitated by navigated tracking of the free acetabular fragment or interposing a patient-specific rotating template to achieve the desired acetabular orientation. Furthermore, all of these systems that were recently described (after 2015) also utilized concomitant preoperative planning software to template the osteotomies and plan the acetabular correction. Failure to achieve appropriate acetabular coverage and version following PAO has been associated with worse long-term outcomes [26, 27]. Although similar post-operative LCEAs were noted in studies that compared computer-assisted and conventional PAO groups [16, 19, 22–25], diverse surgical techniques and study methodology limited the ability to strongly conclude if these computer-assisted modalities increased the accuracy for osteotomies and correction of PAOs.

However, computer-assisted modalities may offer another advantage of decreased intraoperative radiation, as was demonstrated in three studies [16, 19, 23]. While the threshold for an acceptable level of radiation exposure is poorly defined, hip preservation surgeons must balance the clinical necessity of additional imaging versus the risks [28, 29]. This dilemma is magnified in patients undergoing PAO surgery, given the prevalence of symptomatic hip dysplasia in young females [30, 31]. Furthermore, increasing recognition of the radiation risks has been reported for orthopedic surgeons, with recommendations to limit radiation exposure when possible [32, 33].

In hip arthroplasty, the usage of navigation has been associated with an increased accuracy of component positioning, while also having the trade-off of longer surgical times [34]. However, this review observed similar operative times in the studies

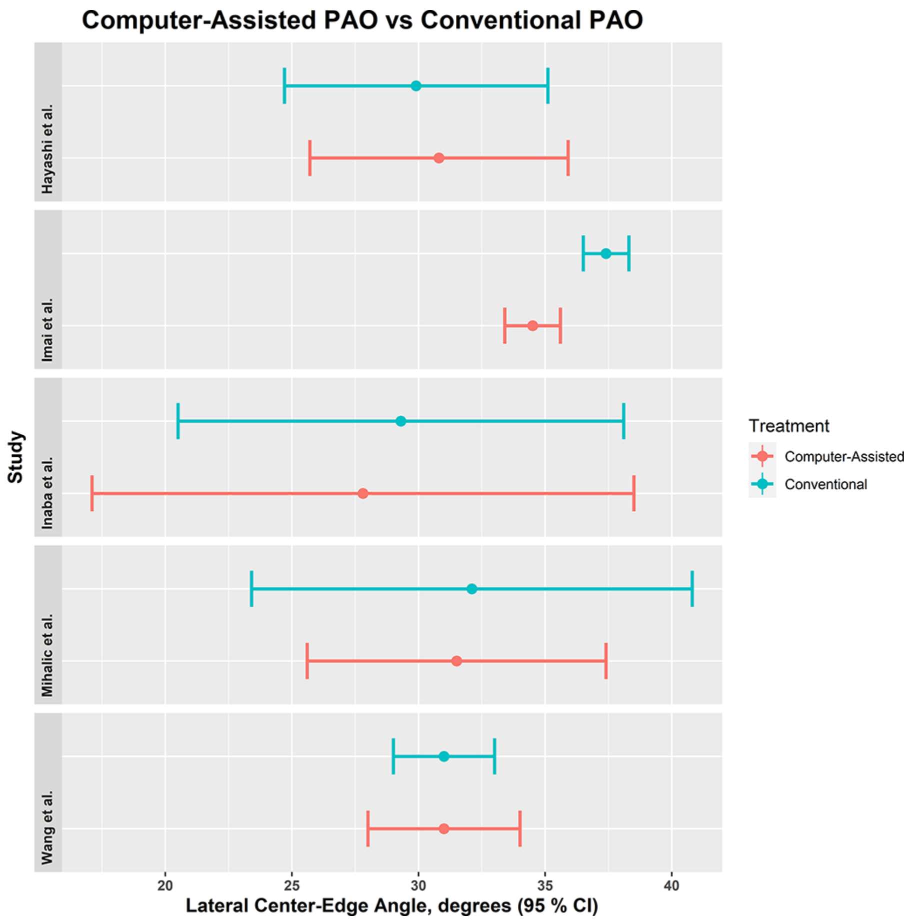

Fig. 5. Graphical depiction of the standardized means for post-operative LCEA (degrees), comparing computer-assisted versus conventional PAO.

that compared navigation-assisted and conventional PAOs [16, 22, 25]. Furthermore, Wang *et al.* [23] reported significantly decreased surgical times when using a patient-specific cutting guide and rotating template. A possible explanation for these findings is that the computer-assisted modalities allowed surgeons to be more efficient with their instrument placement and acetabular correction, rather than relying on repetitive intraoperative assessments with imaging. Given that the surgeons in these studies were high-volume PAO surgeons with experience using the computer-assisted modalities, these results should be interpreted with caution, as they might not extrapolate to lower-volume surgeons who are unfamiliar with navigation or patient-specific guides for PAOs.

Following computer-assisted PAOs, improved PROs were demonstrated at short- to mid-term follow-up in all studies that reported preoperative and post-operative values [12, 21–25]. These findings suggest that computer-assisted modalities do not lead to inferior outcomes after PAOs. A proposed benefit of computer-assisted PAOs is the increased accuracy of the acetabular correction to the desired orientation, optimizing joint contact pressures [35]. However, the clinically significant effects of improved joint kinematics may not be observed at short- to mid-term follow-up [36], and a recent systematic review of 24 studies found that conversion to THA following PAO occurred at a mean of 4.7 years [37]. Therefore, longer follow-up is necessary to determine if computer-assisted modalities improve acetabular correction to a level that translates into clinically relevant results.

Limitations

A limitation of this review was the small number of studies included, which consisted primarily of Level III and IV studies. Furthermore, the heterogeneous operative techniques, surgical settings, computer-assisted modalities and study methodology limited the ability to extrapolate these findings to one specific surgical setting. However, a benefit of this review is the qualitative analysis of these varying factors, giving an overview of the diverse options for computer-assisted techniques in multiple surgical venues. Additionally, an accurate correction of the free fragment during PAO occurs in three dimensions [9], which may not be fully characterized by the two dimensional radiographic metrics that were commonly reported in the included studies. Moreover, these studies primarily included high-volume PAO surgeons at a single institution with experience using their respective computer-assisted modalities, limiting the generalizability of these findings to other surgical settings.

Table IV. *Post-operative outcomes*

Author	*Group*	*Length of follow-up*	*PROs (baseline)*	*PROs (most recent follow-up)*	*Complications*	*Subsequent surgery*
Hayashi *et al.*	Computer-assisted ($n = 30$)	2.1 years	JOA 76.3 ± 9.5 UCLA 6.9 ± 2.0	JOA 98.8 ± 2.1 UCLA 8.9 ± 9.9	Not reported	Not reported
	Conventional ($n = 23$)		JOA 81.8 ± 10.8 UCLA 6.6 ± 1.3	JOA 96.7 ± 3.4 UCLA 7.8 ± 1.9		
Hseih *et al.*	Computer-assisted ($n = 18$)	Minimum 2 years	Merle d'Aubigne and Postel hip score: total 13.3 (range, 10–15); pain 3.5 (range, 2–5); walking 4.8 (range, 2–6); ROM 5.0 (range, 4–6)	Merle d'Aubigne and Postel hip score: total 17.0 (range, 15–18); pain 5.5 (range, 5–6); walking 5.7 (range, 5–6); ROM 5.8 (range, 4–6)	Not reported	Not reported
	Conventional ($n = 18$)	Minimum 2 years	Merle d'Aubigne and Postel hip score: total 13.1 (range, 11–14); pain 3.5 (range, 2–5); walking 4.6 (range, 3–6); ROM 5.0 (range, 4–6)	Merle d'Aubigne and Postel hip score: total 17.2 (range, 15–18); pain 5.8 (range, 4–6); walking 5.6 (range, 4–6); ROM 5.8 (range, 4–6)		
Imai *et al.*	Computer-assisted ($n = 58$)	4.1 ± 0.1 years (range, 3–6)	JOA 74.5 (range, 55–93)	JOA 94.2 (range, 81–100)	0 total (0.0%)	0 total (0.0%)
	Conventional ($n = 40$)	7.3 ± 0.2 years (range, 6–11)	JOA 70.0 (range, 35–90)	JOA 90.7 (range, 50–100)	0 total (0.0%)	5 total (12.5%): 5 THA conversions
Inaba *et al.*	Computer-assisted ($n = 23$)	Not reported	Not reported	Not reported	0 total (0.0%)	Not reported
	Conventional ($n = 23$)				1 total (4.4%): 1 transient femoral nerve palsy	
Langlotz *et al.*	Computer-assisted ($n = 12$)	0.9 years	HHS 66	HHS 77	0 total (0.0%)	Not reported

(continued)

Table IV. (Continued)

Author	*Group*	*Length of follow-up*	*PROs (baseline)*	*PROs (most recent follow-up)*	*Complications*	*Subsequent surgery*
Mihalic *et al.*	Computer-assisted ($n = 30$)	2.9 ± 1.1 years	HHS 50 ± 18	HHS 88 ± 12	2 total (6.7%): 1 delayed wound closure, 1 minor HO (Brooker 1–2)	6 total (20%): 1 THA conversion, 5 symptomatic hardware removals
	Conventional ($n = 10$)	6.2 ± 0.9	HHS 55 ± 17	HHS 86 ± 14	4 total (40%): 1 peripheral neuropraxia, 1 DVT, 1 LFCN neuropathy, 1 minor HO (Brooker 1–2)	2 total (20%): 1 THA conversion, 1 symptomatic hardware removal
Murphy *et al.*	Computer-assisted ($n = 12$)	Minimum 5 years	Not reported	Q Score 89.7 (range, 69–100)	Not reported	2 total (16.7%): 1 THA conversion (at 1 year), 1 symptomatic hardware removal (at 10 months)
Takao *et al.*	Computer-assisted ($n = 25$)	3.2 ± 0.8 years (range, 2.0–5.1)	NPRS 5.6 ± 2.2 (range, 2–10) WOMAC: pain 6.1 ± 4.0 (range, 1–18); stiffness 2.5 ± 2.2 (range, 0–8); physical function 13.8 ± 13.1 (range, 0–43); total 22.6 ± 18.4 (range, 2–69)	NPRS 2.2 ± 2.3 (range, 0–8) WOMAC: pain 2.0 ± 2.3 (range, 0–8); stiffness 0.8 ± 1.4 (range, 0–5); physical function 6.0 ± 8.9 (range, 0–36); total 8.8 ± 11.8 (range, 0–40)	1 total (4.0%): 1 deep infection	Not reported
Wang *et al.*	Computer-assisted ($n = 8$)	Minimum 1 year	HHS 66 ± 5 (range, 61–77) VAS 3.2 ± 0.6 (range, 2.5–4.5)	HHS 94 ± 2 (range, 92–97) VAS 1.0 ± 0.8 (range, 0–2.6)	0 total (0%)	Not reported
	Conventional ($n = 12$)	Minimum 1 year	HHS 67 ± 5 (61–78) VAS 3.0 ± 0.4 (range, 2.6–3.6)	HHS 91 ± 1 (range, 90–94) VAS 1.3 ± 0.9 (range, 0–2.8)	0 total (0%)	Not reported

Data are presented as means ± SD (range, upper limit–lower limit) or *n* (%) unless otherwise noted. All angles are reported as degrees. DVT, deep vein thrombosis; HO, heterotopic ossification; LFCN, lateral femoral cutaneous nerve; NPRS, numeric pain rating scale; ROM, range of motion; UCLA, University of California and Los Angeles activity scale; VAS, visual analog scale; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

CONCLUSION

Computer-assisted modalities for PAO include navigated tracking of the free acetabular fragment and surgical instruments, as well as patient-specific cutting guides and rotating templates. Compared to conventional techniques, decreased intraoperative radiation exposure and similar operative lengths were observed with computer-assisted PAOs, although these results should be interpreted with caution due to heterogeneous operative techniques and surgical settings.

DATA AVAILABILITY

The data underlying this article may be shared on reasonable request to the corresponding author.

AUTHOR CONTRIBUTIONS

A.J.C. contributed to data collection/analysis and writing of the manuscript. R.E.B. contributed to data collection/analysis and writing of the manuscript. S.P. contributed to data collection/analysis and writing of the manuscript. A.E.J. contributed to data interpretation and revision of the manuscript. F.L. contributed to data interpretation and revision of the manuscript. B.G.D. contributed to data interpretation and revision of the manuscript.

CONFLICT OF INTEREST STATEMENT

B.G.D. has had ownership interests in Hinsdale Orthopaedics, the American Hip Institute SCD#3, North Shore Surgical Suites, and Munster Specialty Surgery Center; has received research support from Arthrex, ATI, the Kauffman Foundation, Stryker, and Pacira Pharmaceuticals; has received consulting fees from Adventist Hinsdale Hospital, Arthrex, MAKO Surgical, Medacta, Pacira Pharmaceuticals, and Stryker; has received educational support from Arthrex, Breg, and Medwest; has received speaking fees from Arthrex and Pacira Pharmaceuticals; receives royalties from Amplitude, Arthrex, DJO Global, MAKO Surgical, Medacta, Stryker, and Orthomerica; and is the medical director of Hip Preservation at St. Alexius Medical Center, a clinical instructor at the University of Illinois College of Medicine, and a board member for the American Hip Institute Research Foundation, AANA Learning Center Committee, the Journal of Hip Preservation Surgery, and the Journal of Arthroscopy. F.L. has received royalties from Medacta. A.E.J. has received support for education from Medwest.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was performed in accordance with the ethical standards in the 1964 Declaration of Helsinki. This study was carried out in accordance with relevant regulations of the US Health Insurance Portability and Accountability Act. Details that might disclose the identity of the subjects under study have been omitted. This study was approved by the IRB (IRB ID: 5276). This study was performed at the American Hip Institute Research Foundation.

LEVEL OF EVIDENCE

IV, systematic review of Level II through Level IV studies.

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