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REVIEW ARTICLE

The learning curve for the direct anterior total hip arthroplasty: a systematic review

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Abstract

Background The direct anterior approach (DAA) for total hip arthroplasty (THA) is a muscle-sparing approach thought to have less post-operative pain and quicker recovery, with similar functional outcomes to other approaches. However, it is technically challenging and transitioning surgeons may experience increased complication rates. The purpose of this systematic review is to identify reported learning curves associated with the DAA.

Methods Three databases (MEDLINE, Embase, and Web of Science) were searched using terms including "total hip arthroplasty," "direct anterior approach," and "learning curve." Study characteristics, patient demographics, learning curve analyses, and complications were abstracted.

Results Twenty-one studies met inclusion criteria, with a total of 9738 patients (60% female), an average age of 63.7 years (range: 13–94), body mass index of 27.0 kg/m^2 (range: 16.8–58.9), and follow-up of 19 months (range: 1.5–100). There were five retrospective cohort studies and 13 case series representing fair methodological quality. Six studies depicted a true learning curve, with mean operative time of 156.59 ± 41.71 minutes for the first case, 93.18 ± 14.68 minutes by case 30, and 80.45 ± 12.28 minutes by case 100. Mean complication rate was 20.8 ± 12.7% in early groups and decreased to 7.6 ± 7.1% in late groups.

Conclusion This review demonstrated a substantial learning curve associated with the DAA to THA. Operative time plateaued after approximately 100 cases. Complication rates decreased substantially from early to late groups.

Keywords Total hip arthroplasty · Direct anterior approach · Learning curve · Systematic review

Introduction

Total hip arthroplasty (THA) continues to be one of the most effective and commonly performed orthopaedic procedures, with over 500,000 performed each year in North America and a projected rise to almost 1.5 million by 2040 [1–3]. With the growing demand for minimally invasive surgical methods, there has been a recent resurgence of the direct anterior approach (DAA) to the hip in the context of THA [4]. Though originally described by Hueter, the DAA is more commonly known by the report published by Smith-Petersen in 1917 [5, 6]. This approach uses a true intermuscular, internervous plane to approach the hip, which, along with the size of the skin incision, contributes to its reputation as a minimally invasive technique.

Due to its muscle-sparing nature, proponents of the DAA believe it leads to less post-operative pain and faster recovery times [7–12]; however, it is thought that the functional advantages offered by the DAA are equivalent to other approaches by as early as two weeks post-operatively [7]. Additionally, it is suggested that the DAA leads to decreased post-operative dislocation rates, as the posterior capsule and soft tissues are preserved with this approach [13–15]. Lastly, with shorter average hospital stays due to enhanced early recovery, the use of the DAA has opened the door for outpatient THA [16–18]. Despite its many potential advantages, the use of the DAA is technically challenging and overall complication rates may be higher in DAA THA [19, 20], especially among surgeons new to the approach [21, 22]. This, along with the large number of surgeons transitioning to the DAA, has led to discussion regarding the procedure's learning curve.

Level of Evidence: IV

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The concept of a learning curve for surgical procedures is not a new one. The relationship between operative procedures performed by a surgeon and lower mortality rates was reported in 1979 [23]. This concept of a learning curve in a surgical context was further described as having four stages: (1) a rapid ascent during the early stages of training; (2) a zone of decreasing improvement, where additional experience yields only marginal improvement; (3) a plateau, in which further experience has no effect on the measured outcome; and (4) possible age-related decline in the measured outcome [24]. Due to its increasing popularity and technical challenges, the learning curve of the DAA THA has garnered considerable attention [25–29]. Identifying this learning curve has considerable implications for patient safety, surgical training, and cost-effectiveness as it relates to operative time. The purpose of this systematic review is to identify the reported learning curves associated with the DAA to THA, primarily by analysis of operative time and complications. Additionally, the purpose was to determine, based on the best available evidence, a point on the learning curve after which the surgeon can be considered proficient.

Methods

This systematic review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for conducting and reporting systematic reviews [30]. The study protocol was registered prospectively on The International Prospective Register of Systematic Reviews (PROSPERO) (ID: CRD42020195680).

Search strategy

Three online databases (MEDLINE, Embase, and Web of Science) were searched from database inception to June 25, 2020, for literature addressing the learning curve associated with the use of the DAA for THA. Search terms used to identify eligible studies included "direct anterior approach," "total hip arthroplasty," "learning curve," "clinical competence," "outcome assessment," and "complication" (Appendix).

Study screening

Studies identified during the comprehensive literature search were screened at the title/abstract as well as full-text stages by two reviewers independently and in duplicate using the online software Rayyan (2010, Qatar Computing Research Institute, Doha, Qatar). Any discrepancies at the title/abstract stage were resolved with automatic inclusion into the next stage of screening for more in-depth review. At the full-text stage, discrepancies were discussed and resolved by consensus between the reviewers, and a more senior author was consulted for any remaining discrepancies. In addition, the references of relevant studies were screened manually to identify any eligible studies potentially missed by the database search.

Assessment of study eligibility

The research question and study eligibility criteria were established *a priori*. The inclusion criteria were as follows: (1) all levels of evidence, (2) studies performed on human patients, (3) operative studies using the DAA for THA, and (4) formal discussion or analysis of the learning curve based on the results of the study. Exclusion criteria were (1) review articles, opinion pieces, editorials, or basic science studies, and (2) multiple studies reporting on the same group of patients (only the most recent study is to be included).

Data abstraction

Three reviewers independently extracted data from included studies into a Google Sheet (Google, CA, USA) online collaborative spreadsheet, designed *a priori*, and piloted prior to its use. Collected data included study characteristics, patient demographics, data on the learning curve, and complications both intra-operative and post-operative. Learning curve data was extracted from figures using WebPlotDigitizer (Version 4.3, Pacifica, CA, USA) to estimate values for individual data points.

Quality assessment

The methodological quality of non-randomized studies was evaluated using the Methodological Index for Non-Randomized Studies (MINORS) criteria [31]. Using the MINORS checklist, non-comparative studies can achieve a maximum score of 16, while comparative studies can achieve a maximum score of 24. No literature currently exists for categorizing MINORS scores; however, we categorized the quality of evidence *a priori* based on a previous systematic review by our group: <5 indicated very low quality evidence, 6–9 low quality, 10–14 fair quality, and >14 good quality [32].

Statistical analysis

Inter-class correlation (ICC) was calculated to determine agreement between reviewers on MINORS assessments and studies were assigned the mean score in cases when there was disagreement between reviewers. Descriptive statistics including means, standard deviations, and ranges are presented where applicable. Due to the heterogeneity of existing literature and inconsistency in reported outcomes, meta-analysis was unable to be performed.

Results

Study characteristics

The initial search yielded 2083 studies, 21 of which met the inclusion criteria for this review (Fig. 1) [21, 25, 27–29, 33–48]. These studies, which were published between 2008 and 2020, included five retrospective cohort studies (level 3 evidence) and 13 case series (level 4 evidence) (Table 1). The included studies were completed in North America (10 studies), Europe (8 studies), Asia (2 studies), and Australia (1 study). These studies analyzed the learning curves of 63 surgeons. Main methodology and findings of included studies are described in Table 2.

Study quality

There was excellent overall agreement between assessors for quality assessment scores using the MINORS criteria (ICC=0.945, 95% CI: 0.868–0.977). The included studies had an average MINORS score of 14 ± 3 which indicates a fair quality of evidence of included studies.

Patient demographics

There were 9908 patients included, 60% of which were women. Included patients had an average age of 63.5 years (range: 13–94) and body mass index of 27.1 kg/m^2 (range: 16.79–58.94). The average length of follow-up was 19 months (range: 1.5–100). Most studies used exclusively cementless stems, but four studies also used cemented stems for some cases (range: 1–5% of cases) [29, 33, 39, 40]. Twelve studies used cementless acetabular components [21, 25, 27, 28, 33, 34, 37–39, 41, 43, 48], two used cemented [29, 40], and seven studies did not report the type of acetabular component used [25, 35, 36, 42, 44, 46, 47]. Seven studies used intra-operative fluoroscopy to assist with component positioning [25, 36, 38, 39, 44–46]. Osteoarthritis was the most common indication for THA in most studies, with the exception of two in which femoral neck fractures [37] and osteonecrosis [38] were the most common indications for THA.

Learning curve groups and surgeon experience

All studies investigated the learning curve by grouping consecutive cases and comparing outcomes between the groups. Each study chose slightly different grouping variations, but most frequently studies compared the first number cases to subsequent cases or divided their cases into two equal groups. Groups ranged from 15 cases to 100 cases. Pooled analysis of early and late groups was performed when appropriate. Surgeon experience also varied between studies. Most studies investigated the learning curve in experienced surgeons who had performed hundreds of THAs via alternative approaches.

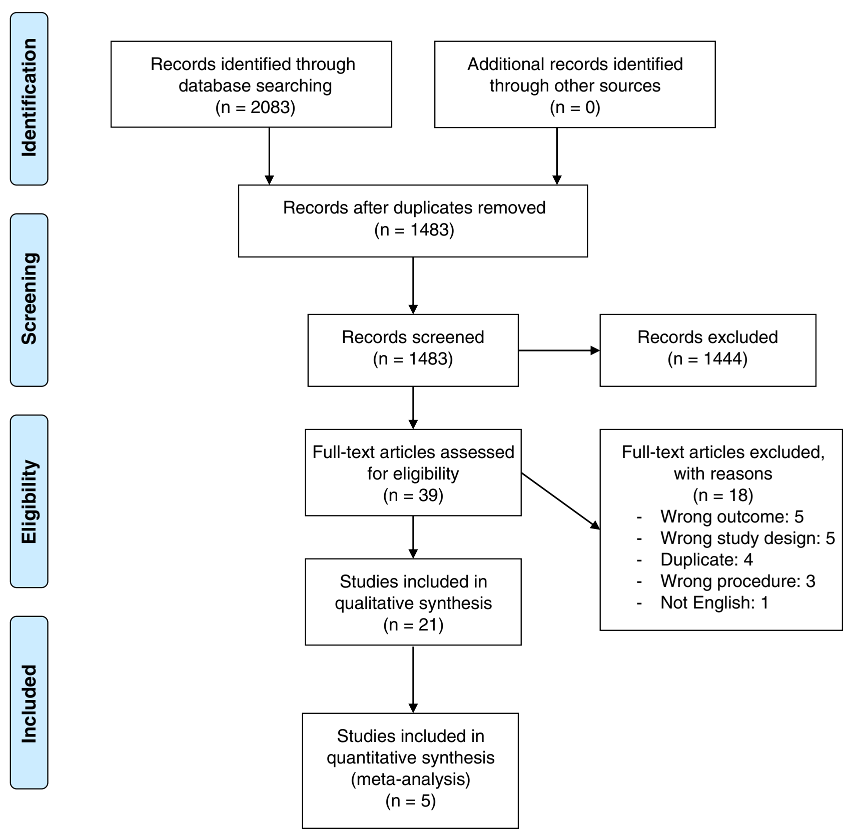

Fig. 1 PRISMA flowchart for the systematic search strategy utilized

Table 1 Characteristics of included studies

Author	Year	Country	Study design	Sample size	Grouping of patients	Mean age (y)	Mean BMI (kg/m^2)	Mean follow-up (months)	# of surgeons	MINORS score
Berndt et al.	2019	Switzerland	Case series	151	1–20, 21–151	64	26	81	5	9
Brun et al.	2018	Norway	Case series	522	1–250, 250–500	67	-	6	15	15.5
de Steiger et al.	2015	Australia	Case series	4138	1–15, 15–30, 31–50, 50–100, >100	-	-	-	13	11.5
Foissey et al.	2020	France	Case series	525	First 20 vs last 20 in series; Sr vs Jr surgeons	66	26	36.2	7	17
Gofton et al.	2020	Canada	Case series	1087	1–15, 16–50, 51–100, >100	61.04	27.5	-	4	12.5
Goytia et al.	2012	USA	Case series	81	1–20, 21–40,41–60, 61–81	58	27.5	24	1	16.5
Hartford et al.	2017	USA	Case series	500	100 case intervals	66	28.4	-	1	12
Kim et al.	2020	Korea	Case series	53	1–10, 11–53	70	23.06	-	1	12
Kong et al.	2019	China	Case series	100	1–50, 51–100	39.5	22.6	3	1	15.5
Masonis et al.	2008	USA	Case series	300	1–100, 101–200, 201–300	58.57	28.7	13.1	1	17
Melman et al.	2015	Netherlands	Case series	182	1–61, 61–122, 123–182	69	28	-	1	13.5
Müller et al.	2014	Switzerland	Case series	150	1–20, 21–150	64	27.4	-	3	9.5
Pirruccio et al.	2020	USA	Retrospective cohort	100	1–10, 1–30, 31–60, 61–100	62.6	25.9	30	1	18.5
Pogliacomi et al.	2012	Italy	Retrospective cohort	30	Last 30 lateral approach vs first 30 DAA	68	27	12	1	18
Schwartz et al.	2016	USA	Retrospective cohort	211	1–40, 41–80, 81–120, 121–160, 161–211	66.3	29.6	3	1	16.5
Seng et al.	2009	USA	Case series	182	3-month intervals: 1–26, 27–85, 86–104, 105–158, 159–162, 163–182	-	-	-	1	14
Spaans et al.	2012	Netherlands	Retrospective cohort	46	1–15, 16–30, 31–46	69	25	12	2	17.5
Stone et al.	2018	USA	Case series	1000	50 case intervals	-	-	24	1	9
Van den Eeden et al.	2018	Belgium	Case series	400	1–200, 201–400	66	24.8	12	1	16
York et al.	2017	USA	Case series	50	1–25, 26–50	57.2	-	8.36	1	10
Zawadsky et al.	2014	USA	Retrospective cohort	100	1–50, 51–100	59.8	29.1	1.5	1	14.5

Abbreviations: BMI, body mass index; DAA, direct anterior approach; Jr, junior; kg, kilograms; m, meters; MINORS, Methodological Index for Non-Randomized Studies; Sr, senior; THA, total hip arthroplasty; USA, United States of America; y, years; #, number

One study compared the learning curve of a senior surgeon to junior surgeons, showing that the learning curve of junior surgeons joined that of the senior surgeon after ten cases [25].

Operative time learning curve

Only six studies reported individual case data to depict a true learning curve, with five reporting on operative time [34, 39, 40, 42, 43] and individual studies reporting on blood loss [43], setup time [40], and component placement [48]. Although five studies reported a learning curve for operative time, each study reported these results slightly differently. Individual studies reported on the first 30 cases [39], the first 50 cases [43], the first 100 cases [34], the first 210 cases [40], and the first 1000 patients [42]. Mean operative time for the first case was 156.59 ± 41.71 min but decreased to 93.18 ± 14.68 minutes by case 30 and 80.45 ± 12.28 min by case 100 (Fig. 2). Although mean operative

Table 2 Summary of included studies main methodology and findings

Author	Title	Journal	Main methodology	Main findings
Berndt et al.	Total hip arthroplasty with accolade/trident through the direct minimally invasive anterior approach without traction table: Learning curve and results after a minimum of 5 years	Orthopaedics and Traumatology: Surgery & Research	Retrospective analysis of first 20 to the next 131 consecutive cases	First 20 cases had higher rates of revision and lower 5-yr survival rates
Brun et al.	The direct anterior minimal invasive approach in total hip replacement: a prospective departmental study on the learning curve	Hip International	Prospective analysis of first 522 cases, comparing every 100 cases	Decreased operative time complication rates, and improved PROMs after first 250 cases
de Steiger et al.	What is the learning curve for the anterior approach for total hip arthroplasty?	Clinical Orthopaedics and Related Research	Retrospective analysis of first 100 cases performed by 68 surgeons	Surgeons who performed 50+ cases had the same revision rates as those who performed 100+
Foissey et al.	Total hip arthroplasty performed by direct anterior approach - Does experience influence the learning curve?	Sicot-J	Retrospective analysis of 525 cases performed by senior and junior surgeons	Senior and junior surgeons had lower complication rates in their last 20 cases than their first 20
Gofton et al.	Ten-year experience with the anterior approach to total hip arthroplasty at a tertiary care center	Journal of Arthroplasty	Retrospective analysis of 1087 hips performed by four senior surgeons	Higher rates of complications and revisions in first 15 cases than after 100 cases
Goytia et al.	Learning curve for the anterior approach total hip arthroplasty	Journal of Surgical Orthopaedic Advances	Prospective analysis of a surgeon’s first 81 cases	Significant decrease in operative time and EBL from first 20 cases to cases 61–81
Hartford et al.	The learning curve for the direct anterior approach for total hip arthroplasty: A single surgeon's first 500 cases	Hip International	Retrospective analysis of a surgeon’s first 500 cases	Decrease in complication and revision rate from first 100 cases to last 100
Kim et al.	Early experience of direct anterior approach total hip arthroplasty: analysis of the first 53 cases	Hip & Pelvis	Retrospective analysis of a surgeon’s first 52 cases	Significant decrease in operative time and EBL from first 10 cases to last 10
Kong et al.	Adopting the direct anterior approach: experience and learning curve in a Chinese patient population	Journal of Orthopaedic Surgery and Research	Retrospective analysis of a surgeon’s first 100 cases	Significant decrease in operative time and complication rate from first 50 cases to second 50
Masonis et al.	Safe and accurate: learning the direct anterior total hip arthroplasty	Orthopedics	Retrospective analysis of a surgeon’s first 300 cases	Operative time decreased significantly from first 100 cases to last 100
Melman et al.	First experiences with the direct anterior approach in lateral decubitus position: learning curve and 1 year complication rate	Hip International	Retrospective analysis of a surgeon’s first 182 cases	Decreased rate of complications from first 60 cases to last 60
Müller et al.	Anterior minimally invasive approach for total hip replacement: five-year survivorship and learning curve	Hip International	Retrospective analysis of 150 cases performed by 3 surgeons	Significant improvement in 5-yr survival rate after first 20 cases
Pirruccio et al.	Safely implementing the direct anterior total hip arthroplasty: a methodological approach to minimizing the learning curve	Journal of the American Academy of Orthopaedic Surgeons	Prospective analysis of a surgeon’s first 100 cases; comparison to last 100 posterior THA	Operative time decreased from first 10 cases to last 40
Pogliacomi et al.	Influence of surgical experience in the learning curve of a new approach in hip replacement: anterior mini-invasive vs. standard lateral	Hip International	Retrospective analysis of a surgeon’s first 30 cases; comparison to 30 lateral THA cases by the same surgeon	Operative time decreased with surgeon experience
Schwartz et al.	Transitioning to the direct anterior approach in total hip arthroplasty: is it safe in the current health care climate?	Journal of Arthroplasty	Retrospective analysis of a surgeon’s first 211 cases; comparison to 201 posterior THA cases by the same surgeon	Operative time decreased with surgeon experience

Table 2 (continued)

Author	Title	Journal	Main methodology	Main findings
Seng et al.	Anterior supine minimally invasive total hip arthroplasty: defining the learning curve	Orthopedic Clinics of North America	Retrospective analysis of a surgeon's first 182 cases; comparison to 77 minimally invasive lateral THAs	Operative time decreased over first 6 months then plateaued
Spaans et al.	High complication rate in the early experience of minimal invasive total hip arthroplasty through the direct anterior approach	Acta Orthopaedica	Retrospective analysis of 46 cases performed by 2 surgeons; comparison to 46 posterolateral THAs	Operative time and EBL decreased from first 15 cases to 31–46
Stone et al.	Evaluation of the learning curve when transitioning from posterolateral to direct anterior hip arthroplasty: a consecutive series of 1000 cases	Journal of Arthroplasty	Retrospective analysis of a surgeon's first 1000 cases	Operative time decreased from first 50 to last 50 cases
Van den Eeden et al.	Learning curve of direct anterior total hip arthroplasty: a single surgeon experience	Acta Orthopaedica Belgica	Comparison of the first 200 cases performed by a surgeon to the next 200 the same surgeon completed in a specialized hip unit	Operative time and EBL decreased from first 50 cases to 50–200
York et al.	Orthopaedic trauma surgeons and direct anterior THA: evaluation of learning curve at a level I academic institution	European Journal of Orthopaedic Surgery and Traumatology	Retrospective analysis of a surgeon's first 50 cases	Operative time decreased from first 25 to second 25 cases
Zawadsky et al.	Early outcome comparison between the direct anterior approach and the mini-incision posterior approach for primary total hip arthroplasty: 150 consecutive cases	Journal of Arthroplasty	Retrospective review of 150 consecutive cases performed by a single surgeon, comparison to 50 mini-posterior approach THAs	Operative time decreased from first 50 to second 50 cases

Abbreviations: PROMs, patient-reported outcome measures; EBL, estimated blood loss; DAA, direct anterior approach; THA, total hip arthroplasty

time did not reach a true plateau, it remained less than 90 minutes for all cases after the 100th case.

All studies that evaluated operative time across the learning curve revealed a downward trend as surgeons became more experienced with the procedure. Most studies reported a statistically significant reduction in operative time in the late group compared to the early group [27, 29, 36–40, 45–47], though two did not reach significance [21, 42]. Mean operative time for all early and late groups was pooled (see Table 3). The grouping of early DAAs had a mean operating time of 109.5 ± 20.7 min (range: 64.7–135.9), whereas it was 82.6 ± 17.3 min (range: 47.4–113.9) in the late group.

Intra-operative outcomes

Seven studies reported on estimated blood loss across the learning curve [21, 27, 36, 37, 39, 41, 47][21, 27, 36, 37, 39, 40, 47]. Three of these studies demonstrated significant reductions in blood loss from early to late groups [27, 36, 37][27, 36, 37], three showed trends toward blood loss reduction that were not statistically significant [21, 39, 47], and one did not change [40]. When early and late groups were pooled, estimated blood loss decreased from 642.5 ± 219.0 mL (range: 400–1071) to 468.6 ± 115.9 mL (range: 347.5–643). Three studies reported on fluoroscopic time during the procedure [36, 38, 39]. Two studies showed a significant reduction in fluoroscopic time between early and late groups

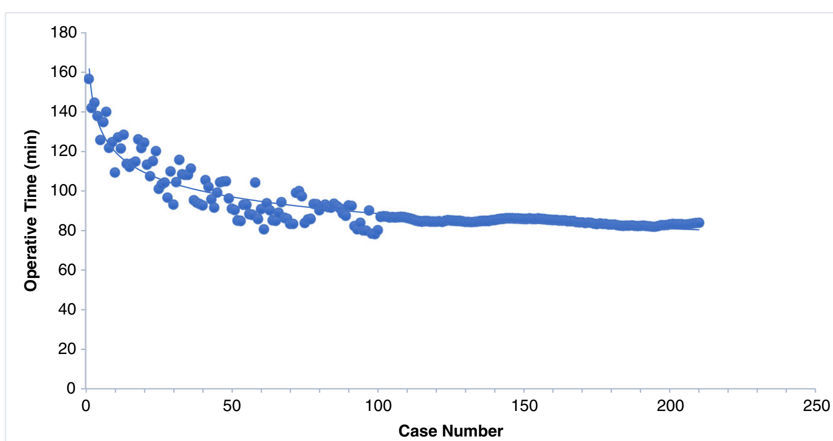

Fig. 2 Learning curve of DAA: operative time by case

Table 3 Summary of pooled outcome data

Outcome	Number of included studies	Early group	Late group
Operative time (min)	13	109.5 ± 20.7	82.6 ± 17.3
Estimated blood loss (ml)	7	642.5 ± 219.0	468.6 ± 115.9
Fluoroscopic time (s)	3	19.5 ± 13.7	11.5 ± 7.5
Length of hospital stay (d)	5	4.4 ± 1.7	4.0 ± 1.3
Acetabular inclination (°)	3	46.8 ± 4.3	47.5 ± 2.9
Acetabular anteversion (°)	2	14.3 ± 1.8	12.9 ± 1.6
Leg length discrepancy (mm)	6	3.2 ± 1.4	2.0 ± 1.2
Pain VAS (0–100)	2	21.3 ± 0.5	14.2 ± 0.2
Harris Hip Score (0–100)	2	89.4 ± 8.8	90.3 ± 8.5
Complication rate (%)	9	20.8 ± 12.7	7.6 ± 7.1
Revision rate (%)	7	7.1 ± 5.0	1.1 ± 0.9
LFCN injury (%)	4	15.0 ± 11.0	5.0 ± 4.8
5-yr implant survival (%)	3	85.9 ± 8.7	96.4 ± 0.6

Abbreviations: d, days; LFCN; lateral femoral cutaneous nerve; min, minutes; ml, milliliters; mm, millimeters; s, seconds; VAS, visual analogue scale; yr, year; °, degrees; %, percentages

[38, 39] and one showed only a downward trend [36]. Mean fluoroscopic time for the early groups was 19.5 ± 13.7 s (range: 4.8–32.1) and decreased to 11.5 ± 7.5 s (range: 2.86–17.0).

Post-operative outcomes

Five studies reported on duration of hospitalization following DAA [21, 27, 38, 47, 48]. Experience performing DAA did not have a significant impact on length of stay in any of the studies. The mean length of stay for the early group of cases was 4.4 ± 1.7 days (range: 2.5–6.6) compared to 4.0 ± 1.3 days (range: 2.5–5.4) for the late group. Three studies reported on acetabular component placement between early and late procedures, though there was no substantial differential between groups [36, 39, 40]. Mean acetabular inclination of early DAAs was 46.8 ± 4.3° (range: 41.9–50) and 47.5 ± 2.9° (range: 44.4–50.1) for late DAAs. Mean acetabular anteversion was 14.3 ± 1.8° (range: 13–15.6) for early DAAs and 12.9 ± 1.6° (range: 11.7–14) for late DAAs. Six studies reported on leg length discrepancy (LLD) [33, 36, 38–40, 44]. The early groups of DAAs had a mean LLD of 3.2 ± 1.4 mm (range: 2–5.04) and late groups of DAAs had a mean LLD of 2.0 ± 1.2 mm (range: 1.07–3.74). Two studies only reported on the number of unacceptable LLDs. One showed a decrease in unacceptable LLDs in the late group from seven to two cases [33] while the other showed no difference between groups [44].

Functional outcomes

Two studies evaluated subjective pain using a visual analogue scale from 0–100 post-operatively, revealing a downward trend of post-operative pain with surgeon experience performing the DAA [29, 48]. Mean pain VAS scores decreased from 21.3 ± 0.5 (range: 20.9–21.6) in early DAAs to 14.2 ± 0.2 (range: 14.0–14.3) in late DAAs. Two studies also compared post-operative Harris Hip Scores (HHS) between early and late groups [36, 38]. Mean HHS did not change significantly, increasing slightly from 89.4 ± 8.8 (range: 83.2–95.7) in early groups to 90.3 ± 8.5 (range: 84.2–96.3) in late groups.

Complications

Eight studies reported increased rates of complications in early groups of DAA procedures compared to late groups [25, 27, 33, 35, 38, 40, 44, 48], while one study did not reveal any difference between groups [46]. Mean complication rate in early groups was 20.8 ± 12.7% (range: 7–44) whereas in late groups it decreased to 7.6 ± 7.1% (range: 0–20) (Fig. 3). Seven studies compared surgical revision rates between early and late procedures [11, 28, 29, 33, 35, 44, 48]. Across early groups, the mean revision rate was 7.1 ± 5.0% (range: 2–15) compared to 1.1 ± 0.9% (range: 0–3) for late groups. Revision rate decreased from early to late groups across all studies. Lateral femoral cutaneous nerve injury was more frequent in early procedures than late, decreasing from 15.0 ± 11.0% (range: 4–25) to 5.0 ± 4.8% (range: 2–12) in late groups [27, 33, 37, 47]. The most common complications during the DAA learning curve were fracture, dislocation, component malposition, and infection [25, 27, 33, 34, 38, 47, 48]. Five-year implant survival was evaluated by three studies, showing a rising trend in implant survival with DAA experience from 85.9 ± 8.7% (range: 78.9–95.6) in early groups to 96.4 ± 0.6% (range: 95.7–96.8) in late groups [34, 35, 41].

Discussion

This systematic review revealed a steep learning curve for the DAA to THA over the first 30 cases and a relative plateau after approximately 100 cases. Mean operative time decreased by more than 50 minutes over the first 30 cases, showing a significant improvement in surgeon skill and comfort with the procedure. This is consistent with previous literature for other orthopaedic procedures, which have often defined the learning

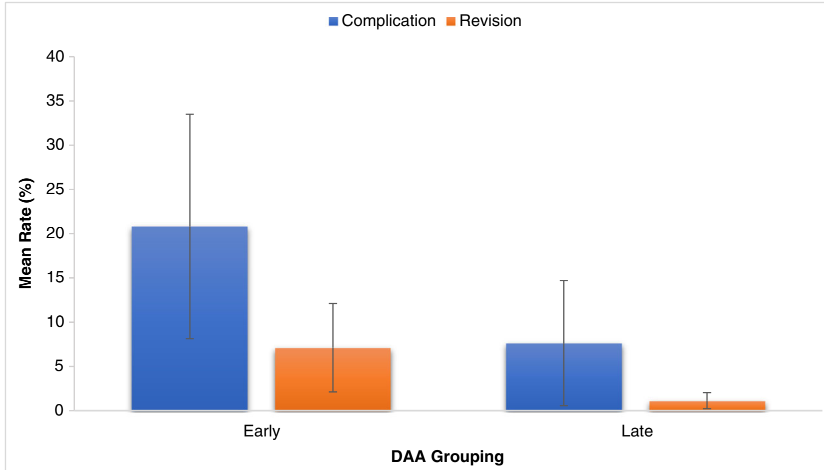

Fig. 3 Comparison of mean complication and revision rates for early and late DAA groupings. Error bars represent standard deviation

curve as the first 30 cases [32, 49, 50]. Although mean operative time was plotted for more than 200 cases, the learning curve never reached a true plateau or inflection point. This suggests that even after performing hundreds of DAA procedures, surgical technique may continue to improve. It should be noted, however, that the learning curve determined by this systematic review only involved the results of two surgeons past 50 cases.

The average operative time for the late groups in this review was 82.6 ± 17.3 minutes. A recent systematic review including 630 675 THA procedures showed that the average operative time for THAs of all approaches was between 90–99 minutes [51]. This review suggests that surgeons who are new to the DAA can reach the average operative time of more traditional THA approaches after approximately 50 cases.

While operative time has been used to evaluate learning curve in many procedures, there is some debate as to the utility of the measure [52, 53]. It is important to consider that there are many factors which may influence operative time, aside from surgeon proficiency. For example, as surgeons become more comfortable performing a procedure, they may take on more technically complex cases which take longer to complete [49]. While operative time is an important outcome with respect to cost-effectiveness of a procedure, small reductions in operative time do not directly lead to patient benefit [52, 54]. Recent literature has shown that each 20 minutes increase in operative time increases the rate of periprosthetic joint infection following total joint arthroplasty by 25% [55]. This suggests that the large reductions in operative time seen early in the learning curve may substantially impact patient outcomes and the small reductions seen past the first 50 cases are less significant. Increased operative time in surgeons who are learning a procedure is likely to represent lack of comfort from the entire surgical team and attention to detail, and thus does not necessarily correlate to patient-centered outcomes such as complication rates [32]. Learning curves may be better evaluated using multiple outcomes rather than operative time alone.

Another key finding from this review was that complication and revision rates showed considerable reductions from early to late groups. Although the specific number of cases needed to significantly reduce complication rates was unable to be determined, the decline in complications and revisions between early and late groups suggests that patient-centered outcomes improve with surgical experience. The average rate of complications in early groups was 20.8 ± 12.7% but ranged from 7 to 44% between individual studies. These complications include fracture, infection, and dislocation, which can require prolonged hospitalization or revision surgery. This trend is also seen in revision rates, five year implant survival, and leg length discrepancy, with improved outcomes as surgeons became more experienced with the procedure. Average rate of revision in the late DAA groups was 1.1 ± 0.9%, which is quite comparable to the rates demonstrated in the literature in alternative approaches beyond the learning curve [19]. The reductions in leg length discrepancy from 3.2 ± 1.4 mm (range: 2–5.04) to 2.0 ± 1.2 mm (range: 1.07–3.74) are especially important, as this is a common reason for litigation and patient dissatisfaction following THA [56, 57]. These increased risks during the learning curve are important for surgeons to discuss with patients when receiving informed consent and consideration should be made to select technically favourable cases as surgeons gain proficiency with the procedure. Female patients with low BMI have been considered technically favourable cases to maximize patient safety during initial procedures [35].

Proper component positioning in THA is important for minimizing the risk of component wear, instability, and impingement, leading to dislocation and revision [58, 59]. Acetabular anteversion is a key aspect of component positioning, with literature showing that ideal anteversion is 15° [60]. Excessive acetabular anteversion is a common concern with the DAA due to the limited view of the anterior acetabular wall [61, 62]. This review showed that mean acetabular anteversion was 14.3 ± 1.8° (range: 13–15.6) for early DAAs and 12.9 ± 1.6° (range: 11.7–14) for late DAAs, suggesting that early DAAs are not at risk of excessive anteversion and that with experience anteversion tends to decrease. The use of intra-operative fluoroscopy in seven of the included studies may help explain the precise component positioning seen in this review.

This systematic review was strengthened by its rigorous methodology. This includes a comprehensive search strategy that involved three major databases and criteria designed to be as inclusive as possible. Reviewer bias was minimized by independently completing each stage of the process in duplicate and automatically including any conflicts. This allowed for the inclusion of 21 studies and 63 surgeons.

The findings of this review are limited by the overall low quality of evidence of included studies. Despite the broad search strategy utilized, the highest level of evidence was level 3 and most included studies were case series. The lack of consecutive case data presented in the included studies was another challenge for this review. Most included studies divided patients into distinct groups of patients with significant heterogeneity between groups. This heterogeneity made it difficult to draw conclusions about the slope of the learning curve beyond early versus late procedures. This limited our ability to analyze the early learning curve for outcomes other than operative time and prevented us from identifying the point at which surgeons reach proficiency.

Future studies should continue to investigate the learning curve beyond the first 50 cases to better characterize the point at which a plateau is reached, suggesting that mastery of the procedure has been achieved. Furthermore, including patient-reported outcomes in these learning curve studies, such as pain and functional scores, would clarify the impact of the DAA learning curve on patient benefit. By reporting continuous case data, future studies could improve the understanding of the learning curve and allow for the integration of risk mitigation strategies as surgeons transition to the procedure.

The DAA is a minimally invasive approach to THA that optimizes post-operative outcomes but is technically complex and has a significant learning curve. This learning curve means that there are increased risks for patients undergoing the procedure by surgeons who are new to the procedure. Operative time reached a relative plateau after approximately 100 cases, suggesting that it takes 100 cases for surgeons to develop proficiency in the DAA to THA.

Appendix

	MEDLINE	Embase	Web of Science
Search strategy	Total hip arthroplasty Direct anterior approach Direct anterior Anterior approach Smith Petersen Smith-Petersen Learning curve Learning Clinical competence Treatment outcome Experience Motor skills Outcome Outcome assessment Complication Intraoperative complications Postoperative complications 2 OR 3 OR 4 OR 5 OR 6 7 OR 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14 OR 15 OR 16 OR 17 1 AND 18 AND 19	Total hip arthroplasty Direct anterior approach Direct anterior Anterior approach Smith Petersen Smith-Petersen Learning curve Learning Clinical competence Treatment outcome Experience Motor skills Outcome Outcome assessment Complication Intraoperative complications Postoperative complications 2 OR 3 OR 4 OR 5 OR 6 7 OR 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14 OR 15 OR 16 OR 17 1 AND 18 AND 19	(((((direct anterior approach) OR direct anterior) OR anterior approach) OR Smith Petersen) OR Smith-Petersen) AND (total hip arthroplasty) AND (((((((((((learning curve) OR learning) OR clinical competence) OR treatment outcome) OR experience) OR motor skills) OR outcome) OR outcome assessment) OR complication) OR intraoperative complications) OR postoperative complications)
Number of articles retrieved	307	528	947

Author contributions LN and LG performed study screening and data extraction and assessed study quality. LN and KG drafted the manuscript. SE designed the study and coordinated data extraction and manuscript preparation. VK edited the manuscript and provided key expert input. All authors read and approved the final manuscript.

Data and materials availability This submission represents original work that has not been previously published and is not under consideration for publication elsewhere.

Declarations

Ethics approval Ethics approval was not required for this systematic review.

Consent to participate and consent for publication As this was a systematic review, data from individual participants was not obtained and will not be published.

Competing interests Author VK is a paid consultant for Stryker Canada and Zimmer Biomet. The other authors have no competing interests to disclose.

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