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Review

Biomechanical changes and recovery of gait function after total hip arthroplasty for osteoarthritis: a systematic review and meta-analysis

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SUMMARY

Objective: To determine the change in walking gait biomechanics after total hip arthroplasty (THA) for osteoarthritis (OA) compared to the pre-operative gait status, and to compare the recovery of gait following THA with healthy individuals.
Methods: Systematic review with meta-analysis of studies investigating changes in gait biomechanics after THA compared to (1) preoperative levels and (2) healthy individuals. Data were pooled at commonly reported time points and standardised mean differences (SMDs) were calculated in meta-analyses for spatiotemporal, kinematic and kinetic parameters.
Results: Seventy-four studies with a total of 2,477 patients were included. At 6 weeks postoperative, increases were evident for walking speed (*SMD*: 0.32, 95% confidence intervals (CI) 0.14, 0.50), stride length (*SMD*: 0.40, 95% CI 0.19, 0.61), step length (*SMD*: 0.41, 95% CI 0.23, 0.59), and transverse plane hip range of motion (ROM) (*SMD*: 0.36, 95% CI 0.05, 0.67) compared to pre-operative gait. Sagittal, coronal and transverse hip ROM was significantly increased at 3 months (*SMDs*: 0.50 to 1.07). At 12 months postoperative, patients demonstrated deficits compared with healthy individuals for walking speed (*SMD*: −0.59, 95% CI −1.08 to −0.11), stride length (*SMD*: −1.27, 95% CI -1.63, −0.91), single limb support time (*SMD*: −0.82, 95% CI −1.23, −0.41) and sagittal plane hip ROM (*SMD*: −1.16, 95% CI −1.83, −0.49). Risk of bias scores ranged from seven to 24 out of 26.
Conclusions: Following THA for OA, early improvements were demonstrated for spatiotemporal and kinematic gait patterns compared to the pre-operative levels. Deficits were still observed in THA patients compared to healthy individuals at 12 months.
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Introduction

Osteoarthritis (OA) of the hip is a common chronic condition responsible for significant pain and disability, with approximately 4–9% of adults over the age of 45 living with symptomatic hip OA[1,2]. Diagnosis of symptomatic OA is the principal indication for total hip arthroplasty (THA), which is the treatment for individuals with end-stage OA when conservative therapies to manage symptoms have been exhausted. The demand for THA is estimated to rise substantially in the next decade, to approximately half a million primary THAs per year by 2030 in the United States[3]. Hip OA commonly affects a patient's function causing difficulty in walking where altered gait biomechanics are observed, particularly in individuals with severe stage disease who are candidates for THA[4]. Whilst THA is a successful procedure, attributed to the long-term survivorship of the implant and alleviation of chronic joint pain, aberrant pre-operative gait patterns may persist following THA, despite improvements in self-reported measures of pain and physical function[5,6].

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Two recent systematic reviews[7,8] compared outcomes in walking gait following primary THA to that of healthy individuals and identified lower walking speed and stride length, lower sagittal and coronal plane hip joint range of motion (ROM), and lower peak hip abduction moment. Whilst these reviews provide a recent comparison of THA patients to that of healthy individuals, the pre-operative functional status of patients were not considered. The nature of gait abnormalities prior to the joint replacement must be considered due to the association between pre- and post-operative gait status[9]. Furthermore, reporting of post-operative gait abnormalities compared with healthy individuals may inadequately represent the changes after THA if relative change to pre-operative status is not considered as end-stage OA patients present with altered gait kinematics compared to healthy individuals which may persist following surgery[5]. A range of time points, from 6 weeks to 24 months[10,11] have been used to investigate changes in gait biomechanics following THA for OA. To date, no review has synthesised the available evidence at commonly reported time points to identify the change from pre-to post-operative gait in people with OA following THA, and compare the results to healthy individuals to better understand the trajectory of change and recovery in gait function after THA. Therefore, the aims of this systematic review were to determine the change in gait biomechanics after THA compared to the pre-operative gait status; and to compare the recovery of gait following THA with healthy individuals.

Methods

The findings of this review are reported in accordance with the Preferred Reporting Items for Systematic Reviews and meta-analyses (PRISMA) statement guidelines (Supplementary File 1)[12]. The protocol for the review was registered with the International Prospective register for Systematic Reviews (PROSPERO; registration no. CRD 42016035904).

Search strategy

The Population, Intervention, Comparison and Outcome (PICO) framework was used to define the search strategy, in consultation with an academic librarian[13]. An electronic search of the following databases was performed with no date restrictions: PubMed, MEDLINE, CINAHL, The Cochrane Library, Embase, Scopus, Web of science, SportDiscus and Health collection. Keywords were matched with exploded MeSH terms to generate themes around THA, biomechanics and gait (Supplementary File 2). Variations of electromyography and stair climbing were included as an outcome in the search as it was anticipated walking gait data might be included in studies of this kind. Database searching was performed by two authors (JB and JA) and agreement was required on the number of articles retrieved from each database before proceeding. Search alerts were created for each database to identify articles published after the initial search (up to January 1, 2017). Conference abstracts and reference lists of review and final included articles were manually searched to identify additional articles. Citations retrieved from the searches were uploaded to an online systematic review platform (Covidence)[14] for screening. Two reviewers (JB and MN) independently screened titles and abstracts and any conflicts were resolved by discussion, or by the opinion of a third researcher (JA) if consensus was not reached. Titles that met the eligibility criteria were then obtained as full manuscripts and reviewed independently by two reviewers (JB and MN). Disagreements were managed using the same process from the screening stage.

Eligibility criteria

Articles were eligible for inclusion in this review when they satisfied the following criteria: (1) adults aged ≥18 years undergoing primary unilateral THA; (2) osteoarthritis was the primary indication for THA; (3) studies reporting the change in gait biomechanics (spatiotemporal, kinematics, kinetics) from pre-to post-operative or comparing THA patients following surgery to matched healthy individuals; (4) 2D or 3D motion analysis techniques (including ground reaction forces) were used to measure level walking at a self-selected speed; and (5) participants could perform the task unaided. Studies using motion capture systems, force platforms, accelerometers, instrumented treadmills or instrumented shoes were all included in this review. Spatiotemporal data collected from a hand-held timepiece (e.g., stopwatch) were excluded. Studies investigating the effect of physical rehabilitation on gait outcomes were excluded unless they included a conventional THA group who did not receive the intervention. Studies including participants who did not undergo THA (e.g., hip resurfacing) or participants with a history of other lower limb joint disease or surgeries (knee, ankle or contralateral hip) were not eligible.

Outcome measures and data extraction

A custom data-extraction spreadsheet was used to extract numerical data from all studies. The first author extracted the data (JSB), and a second author (JBA) verified the data were extracted accurately from the studies that were used in the meta-analysis. The primary outcome measures for this review were spatiotemporal, kinematic (joint angles) and kinetic parameters (e.g., external joint moments) reported during level walking. Means and standard deviation (SD)s for all gait parameters were extracted for the pre-operative and follow-up time points, and from healthy control groups, when available. Extraction of joint kinematic and kinetic parameters were limited to the affected hip. The following information on patient and surgical characteristics was also extracted from each study: study design, sample size, age, gender, body mass index (BMI), severity of osteoarthritis, and surgical approach.

Data synthesis and analysis

As numerous gait variables across multiple time points were expected, a structured process was undertaken to synthesise the results on the most commonly reported variables and time-points. Studies typically report a mean follow-up or multiple post-operative time points at 6 weeks, 3 months, 6 months and 12 months. Where studies reported a mean that was close to these time points (within 1 week for time points <6 months, and 3 months for time points >6 months) data were merged to the closest common time-point to facilitate comparison across studies. No studies were excluded during this process.

When adequate data were reported, standardised mean differences (SMDs) were calculated using the pooled SD for the biomechanical parameters between either the pre and post-operative time points (preoperative as the reference) or postoperative vs control group. Where not available, the standard error of the mean difference were estimated from *P* values using the equivalent T-statistic[15]. When this was not possible, the standard error of the mean difference was estimated using the most conservative correlation estimate from other studies[15], and the stability of this approach was assessed through a sensitivity analysis where the correlation estimate was set to zero to determine the impact on the magnitude of the pooled effect. Where study results were reported as medians and ranges or interquartile ranges, authors were contacted twice to obtain the mean and SD. When not provided, data were transformed to the mean and SD[16]. For the meta-analysis, pooled estimates and 95% confidence intervals (CI) for standardised mean differences were calculated using a random effects model in Review Manager software (RevMan, v5.2, Cochrane Collaboration, Oxford UK). Statistical significance was set at $P < 0.05$. All data were extracted and the pooled effect size estimates were computed when at least two studies reported the same gait variable at the same time point. The magnitude of the overall effect was quantified as trivial (<0.2), small (0.2–0.6), moderate (0.61–1.2), large (1.21–2.0) and very large (>2.0)[16]. Where studies presented data on more than one surgical approach instead of the entire THA cohort, a separate effect size was determined for each surgical group[16].

Heterogeneity was assessed using the I^2 and Cochran's Q statistics[17]. Where heterogeneity was statistically significant ($P < 0.05$), potential explanatory variables contributing to heterogeneity were assessed using linear regression, which was performed using six study characteristics identified *a priori* including age, BMI, sample size, surgical approach, gender and risk of bias score. The regression was only performed when ≥10 studies reported on a gait parameter at a time point[18]. Potential publication bias was examined using contour enhanced funnel plots and Egger's regression test using STATA (v14, Statacorp, USA).

Methodological risk of bias

Methodological risk of bias of studies was performed through merging three established checklists specific to gait analysis and surgical intervention studies (Supplementary File 4)[19–21]. The recommended scoring criteria from each tool were maintained resulting in a total of 20 items with a possible maximum score range of 0–26, with higher scores indicating a reduced risk of bias. The scoring was carried out by two independent reviewers (JB and MN), with any disagreements resolved with the opinion of a third reviewer if required. Inter-rater agreement for each item of the risk of bias tool was evaluated using the Kappa (κ) statistic. The risk of bias scores was included in the meta-regression to investigate if study bias contributed to heterogeneity. Based on the results of the meta-analysis (effect size), statistical heterogeneity (I^2) and risk of bias scores, of the strength of evidence for changes in each outcome variable at each time point was designated as per Van Tulder *et al.* 2003[22]: (1) strong evidence derived from three or more studies, including a minimum of two high-quality studies that were statistically homogenous (I^2 $P \geq 0.05$); (2) moderate evidence derived from multiple studies that were statistically heterogeneous and where the pooled result was statistically significant, including at least one high-quality study from the risk of bias score; or from multiple moderate or low-quality studies which were statistically homogenous; (3) limited evidence provided by results from one high-quality study or multiple moderate-quality or low-quality studies that are statistically heterogeneous; (4) very limited evidence provided by results from one moderate-quality or low-quality study; and (5) no evidence where the pooled effect was insignificant and derived from multiple statistically heterogeneous studies (regardless of study quality from the risk of bias score).

Results

Study selection and characteristics

The electronic database search yielded 3,415 articles. After applying the eligibility criteria and searching of reference lists, 74 studies were retained and 46 were included in the meta-analysis (Fig. 1). Of the 74 included studies, 21 were prospective cohort studies, 21 case series studies, 29 case–control studies, and three randomised controlled trials (Table I).

Patient and surgical characteristics

There were 2,477 patients from 74 studies with a mean age of 59.7 SD 7.4 years, BMI of 28.7 SD 3.6 kg/m^2 and 46% were female (Table I). Post-operative follow-up ranged from 2 days to 6 years, with the most common time-points being 6 weeks, 3 months, 6 months, 12 months and 24 months. Only two studies[37,50] reported the radiographic severity of OA prior to surgery[93]. The direct lateral and posterior surgical approaches were the most frequently used among the included studies ($n = 17$ and $n = 16$, respectively), followed by the anterolateral ($n = 13$) and direct anterior ($n = 10$).

Outcome measures

A total of 20 spatiotemporal, 56 kinematic and 54 kinetic variables were identified (Fig. 1). A total of nine spatiotemporal and six kinematic variables met the requirements for meta-analysis in pre-post comparisons, while eight variables for both domains met the criteria for post vs control. Only one kinetic variable was reported by ≥2 studies comparing postoperative THA patients to healthy controls (peak hip abduction moment). Five authors provided extra data upon request[23,29,35,62,83]. A summary of findings for each gait parameter in the meta-analysis at each time-point is provided in Table II, with detailed information on the magnitude of effects and strength of evidence provided below.

Spatiotemporal: comparison to pre-operative level

Pooled data indicated there was moderate evidence of increased walking speed at 6 weeks (SMD: 0.32, $P = 0.0006$), 3 months (SMD: 0.78, $P < 0.001$) and 6 months (SMD: 0.97, $P < 0.001$), with large changes at 12 months (SMD: 1.28, $P < 0.001$) [Fig. 2(A)]. At 6 weeks, there was a small change in step length (SMD 0.41, $P < 0.001$) [Fig. 3(A)] and stride length (SMD: 0.40, $P < 0.001$) (Supplementary File 3), which was also present at 3 months (SMD: 0.52, $P < 0.001$; and SMD: 0.63, $P < 0.001$), with larger changes in step length at 6 months (SMD: 0.90, $P < 0.001$). There were trivial changes in step width at 6 weeks (SMD: −0.07, $P = 0.57$) and 3 months (SMD: 0.02, $P = 0.96$), with moderate evidence from five studies to suggest that cadence did not change at 6 months (SMD: −0.08, $P = 0.87$) (Supplementary File 3).

Spatiotemporal: comparison to controls

At 6 weeks post-THA there was moderate evidence demonstrating a large deficit in walking speed in THA patients compared with healthy individuals (SMD: −1.81, $P < 0.001$), which persisted but reduced in magnitude at 3 months (SMD: −1.22, $P < 0.001$), 6 months (SMD: −0.69, $P < 0.001$), and 12 months (SMD: −0.59, $P = 0.02$). Two studies provided limited evidence of a small deficit in walking speed at 24 months (SMD: −0.57, $P < 0.007$) [Fig. 2(B)].

Deficits of reducing magnitude were observed in step length compared to healthy individuals at 6 weeks (SMD: −1.36, $P < 0.001$), 3 months (SMD: −0.88, $P < 0.001$), and 6 months (SMD: −0.35, $P = 0.04$), also persisting at 12 months post-THA (SMD: −0.54, $P = 0.25$) [Fig. 3(B)]. Marked deficits in stride length were also evident, with large effect sizes at 6 weeks (SMD: −1.90, $P < 0.001$) and 3 months (SMD: −1.60, $P < 0.001$) with a large improvement in THA patients between 3 and 6 months, but still a moderate deficit at 6 months (SMD: −0.78, $P < 0.001$). However, the same magnitude was not observed as compared to healthy individuals at 12 months (SMD: −1.27, $P < 0.001$).

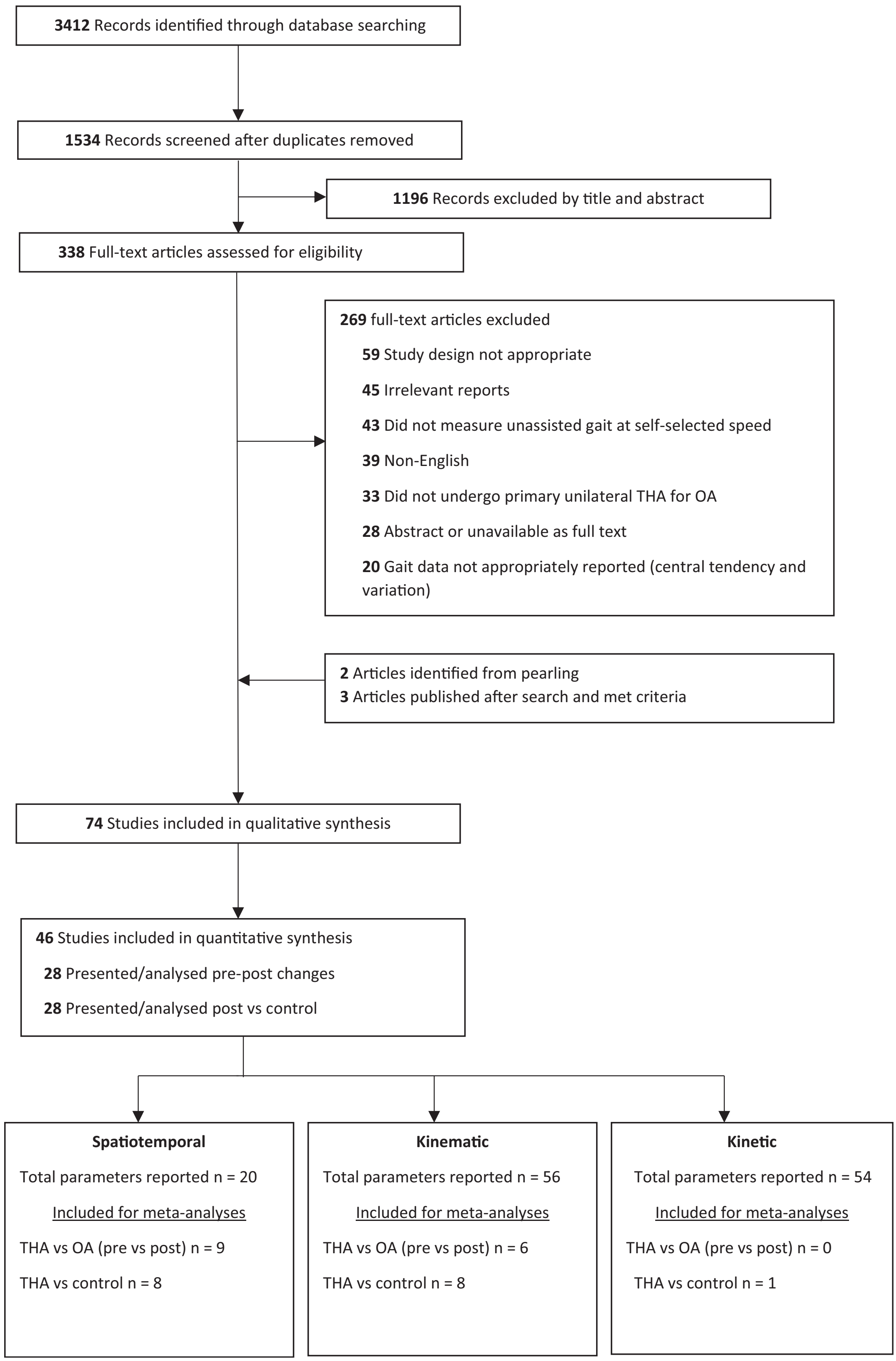

Fig. 1. Flowchart of study selection process.

Table I
Study and patient characteristics

Author (year)	Study design	Study analyses		Sample size ($n =$)		Mean age, SD (years)		Mean BMI, SD (kg/m^2)		Surgical approach	Follow-up time point(s)	QI Score (of 26)
		Pre vs post	Post vs control	Patients (THA)	Controls	Patients (THA)	Controls	Patients (THA)	Controls			
Agostini *et al.* 2014[23]	Case control		✓	20	20	66.1 ± 7.2	65.4 ± 5.1	M = 26.1 ± 2.1; F = 27.7 ± 5.0	M = 24.4 ± 3; F = 23.2 ± 2.5	Posterolateral	3 mo, 6 mo, 12 mo	22
Ajemian *et al.* 2004[24]	Case series	✓		11	N/A	62.6 ± 8.6	N/A	NR	N/A	Not specified	Pre-op, 4 mo, 8 mo	12
Aminian *et al.* 1999[25]	Case series	✓		12	N/A	64.5 ± 8.7	N/A	27.8 ± 2	N/A	Not specified	Not specified	11
Atallah *et al.* 2014[26]	Case control		✓	17	14	65.9 ± 6.5	39.7 ± 17	NR	NR	Not specified	Not specified	15
Beaulieu *et al.* 2010[27]	Case control		✓	20	20	66.2 ± 6.7	63.5 ± 4.4	27.2 ± 5	24.9 ± 3.5	Lateral	6-15 mo	19
Behery and Foucher 2014[28]	Case series	✓		125	N/A	61 ± 10	N/A	28.2 ± 5	N/A	Not specified	Pre-op, 15 mo	7
Bennett *et al.* 2008[29]	Case control		✓	134	10	74.4 ± 2.2	64 ± 3.6	NR	NR	Posterior	9-10 mo	18
Bennett *et al.* 2006[30]	RCT	✓	✓	a: 8 b: 9	10	a: 60.8 ± 5.8 b: 60.1 ± 6.2	64 ± 3.6	a: NR b: NR	NR	a: Posterior b: Posterior (small incision)	Pre-op, 1.38 mo	14
Berman *et al.* 1991[31]	Prospective cohort	✓	✓	21	91	NR	NR	NR	NR	Anterolateral	Pre-op, 0–4 mo, 5–8 mo, 9–12 mo, 13–18 mo	11
Bhargava *et al.* 2007[32]	Case control		✓	20	NR	51.6 (SD NR)	NR	NR	NR	Posterior	6-51 mo	15
Bianchi *et al.* 2012[33]	Case series	✓		a: 19 b: 17 c: 19	N/A	a: 64.4 ± 4 b: 65.9 ± 4 c: 65.2 ± 3.5	N/A	a: 27.5 ± 3.7 b: 27.1 ± 3.7 c: 26.1 ± 4	N/A	a: Posterolateral (28 mm head) b: Posterolateral (36 mm head) c: Posterolateral (≥42 mm head)	Pre-op, 2 mo, 4 mo	21
Bouffard *et al.* 2011[34]	Case control		✓	12	11	50.8 ± 6.1	45.7 ± 8.2	26.7 ± 4.7	26.3 ± 3	Posterior (large diameter head)	12 mo	21
Casartelli *et al.* 2013[35]	Case control		✓	26	26	65 ± 8		NR		Posterior & anterior[≠]	6 mo	21
Cichy *et al.* 2008[36]	Case series	✓		30	N/A	63.6 ± 8.9	N/A	NR	N/A	Anterolateral	Pre-op, 1 mo	17
Colgan *et al.* 2016[37]	Prospective cohort	✓	✓	10	NR	55.4 ± 7	NR	27.1 ± 2.3	NR	Anterolateral	Pre-op, 8 weeks	19
da Cunha *et al.* 2016[38]	Case series	✓		93	N/A	59.7 ± 11.3	N/A	28.2 ± 4.7	N/A	Lateral	Pre-op, 3 mo	20
Foucher 2016[39]	Case series	✓		145	N/A	61 ± 10	N/A	28.5 ± 5	N/A	Not specified	Pre-op, 12 mo	17
Foucher *et al.* 2015[9]	Case series	✓		145	N/A	61 ± 10	N/A	28 ± 5	N/A	Not specified	Pre-op, 14 mo	17
Foucher *et al.* 2007[5]	Prospective cohort	✓	✓	28	25	63.6 ± 7.1	57.6 ± 7.7	NR	NR	Posterior & lateral[≠]	Pre-op, 14 mo	17
Foucher *et al.* 2010[40]	Case control		✓	26	24	60 ± 9	54 ± 6	NR	NR	Not specified	3 weeks, 12 mo	15
Foucher *et al.* 2011[41]	RCT	✓	✓	a: 13 b: 13	25	a: 57 ± 8 b: 63 ± 9	54 ± 6	a: 27 ± 3 b: 27 ± 3	28 ± 6	a: Anterolateral b: Two incision (anterior and buttock)	3 weeks, 3 mo, 6 mo, 12 mo	23
Holnapy *et al.* 2013[42]	Prospective cohort	✓	✓	a: 25 b: 22 c: 25	45	a: M = 60.1 ± 2.4; F = 59.9 ± 3.4 b: M = 61.3 ± 3.4; F = 62.2 ± 2.4 c: M = 61.2 ± 2.9; F = 60.8 ± 3.0	M = 60.9 ± 3.2; F = 60.4 ± 4.1	a: M = 30.3 ± 3.4; F = 30.1 ± 3.1 b: M = 30.7 ± 2.8; F = 29.8 ± 3.3 c: M = 31.3 ± 3.4; F = 28.9 ± 2.7	M = 24.3 ± 2.8; F = 25.3 ± 2.4	a: Lateral b: Anterolateral c: Posterior	Pre-op, 3 mo, 6 mo	21
Horstmann *et al.* 2013[43]	Prospective cohort	✓	✓	52	24	58 ± 9	54 ± 6.6	NR	NR	Lateral	Pre-op, 6 mo	19
Husby *et al.* 2009[44]	Case series	✓		12	N/A	56 ± 8	N/A	28.2 ± 6.5	N/A	Lateral	Pre-op, 1 week, 5 weeks	24
Isobe *et al.* 1998[45]	Case series	✓		31	N/A	59.5 ± 8.8	N/A	NR	N/A	Not specified		15

(*continued on next page*)

Table I (*continued*)

Author (year)	Study design	Study analyses		Sample size ($n =$)		Mean age, SD (years)		Mean BMI, SD (kg/m^2)		Surgical approach	Follow-up time point(s)	QI Score (of 26)
		Pre vs post	Post vs control	Patients (THA)	Controls	Patients (THA)	Controls	Patients (THA)	Controls			
											Pre-op, 6 mo, 12 mo, 18 mo, 2 y, 3 y, 4 y, 5 y, 6 y	
Jensen *et al.* 2015[46]	Prospective cohort	✓	✓	19	20	55 ± 6	57 ± 7	28.4 ± 2.8	25.6 ± 2.9	Posterolateral	Pre-op, 2 mo, 6 mo	22
Jensen *et al.* 2014[47]	Case series	✓		38	N/A	56 ± 5.6	N/A	27.8 ± 3.6	N/A	Not specified	Pre-op, 2 mo, 6 mo	11
Judd *et al.* 2015[48]	Case series	✓		5	N/A	62.4 ± 7.3	N/A	31.84 ± 4.3	N/A	Posterior	Pre-op, 8 wk	19
Kanzaki *et al.* 2008[49]	Case control		✓	9	11	46.3 ± 12.4	48.9 ± 8.2	20.6 ± 2.5	19.6 ± 1.7	Anterolateral (Dall's)	4 wk, 6 mo	18
Kiss *et al.* 2012[50]	Prospective cohort	✓	✓	a: 40 b: 40	40	a: 71.3 ± 3.7 b: 70.1 ± 1.4	70.8 ± 3.1	a: 29.9 ± 2.4 b: 29.8 ± 1.6	25.6 ± 3.8	a: Lateral b: Anterolateral	Pre-op, 3 mo, 6 mo, 12 mo	23
Klausmeier *et al.* 2010[51]	Prospective cohort	✓	✓	a: 11 b: 12	10	a: 57 ± 7.3 b: 56.9 ± 3.3	59.9 ± 5.3	a: 31.1 ± 4.1 b: 32 ± 5.1	26.3 ± 3.9	a: Anterolateral b: Anterior	Pre-op, 6 wk, 4 mo	21
Krych *et al.* 2011[52]	RCT	✓		a: 8 b: 11	N/A	a: 64.5 ± 13.4 b: 65.64 ± 12.1	N/A	a: 29.38 ± 6.5 b: 28.45 ± 3.4	N/A	a: Posterior (mini-incision) b: Two incision (anterior and buttock)	Pre-op, 2 mo, 12 mo	21
Krych *et al.* 2010[53]	Case series	✓		Total 21 a: 10 b 11	N/A	Total 63 ± 13 a: NR b: NR	N/A	Total 30 ± 6 a: NR b: NR	N/A	a: Posterior (mini-incision) b: Two incision (anterior and buttock)	Pre-op, 6 wk	15
Lavigne *et al.* 2010[54]	Randomised double-blind	✓	✓	24	14	49.8 ± 7.3	44.4 ± 6.3	27.8 ± 3.9	25.8 ± 2.9	Posterior	Pre-op 3 mo, 6 mo, 12 mo	24
Lenaerts *et al.* 2009[55]	Case series	✓		20	N/A	63 ± 9.8	N/A	27.4 ± 3.9	N/A	Lateral	Pre-op, 6 wk	15
Li *et al.* 2015[56]	Case control		✓	15	15	64 ± 2.7	58 ± 1.5	30.7 ± 1.5	24.5 ± 0.7	Not specified	>12 mo	14
Li *et al.* 2014[57]	Case control		✓	15	38	64.27 ± 2.8	44.97 ± 2	30.74 ± 1.5	24.72 ± 0.4	Anterior	>12 mo	14
Loizeau *et al.* 1995[58]	Case control		✓	4	4	67.3 ± 8	58.9 ± 8.9	NR	NR	Not specified	3.8 y	16
Lugade *et al.* 2008[59]	Prospective cohort	✓	✓	20	10	57 ± 5.2	59.9 ± 5.3	31.9 ± 4.3	26.3 ± 3.9	Anterior & lateral[≠]	Pre-op, 6 wk, 4 months	22
Lugade *et al.* 2010[60]	Prospective cohort	✓	✓	a: 12 b:11	10	a: 56.9 ± 3.4 b: 57 ± 7.3	59.9 ± 5.3	a: 32 ± 5.1 b: 31.1 ± 4.1	26.3 ± 3.9	a: Anterior b: Anterolateral	Pre-op, 6 wk, 4 mo	22
Madsen *et al.* 2004[61]	Case control		✓	a: 10 b: 10	9	a: 60.7 ± 8.4 b: 63.6 ± 8	54 ± 9.5	a: NR b: NR	NR	a: Anterolateral b: Posterolateral	6 mo	20
Maffiuletti *et al.* 2009[62]	Case control		✓	a: 17 b: 17	17	a: 69 ± 5 b: 68 ± 6	69 ± 4	a: 27.2 ± 4.2 b: 25.6 ± 3.3	25.5 ± 2.7	a: Posterior b: Anterior	6 mo	21
Mantovani *et al.* 2012[63]	Case control		✓	a: 20 b: 20	20	a: 60.5 ± 6 b: 66.2 ± 6.7	63.5 ± 4.4	a: 28.5 ± 4.9 b: 27.2 ± 5	24.9 ± 3.5	a: Anterior b: Lateral	11 mo 10 mo	15
Martinez-Ramirez *et al.* 2014[64]	Case series	✓		19	N/A	62 ± 9	N/A	NR	N/A	Not specified	Pre-op, 6–8 mo	17
Mayr *et al.* 2009[65]	Prospective cohort	✓	✓	a: 16 b: 17	20	a: 66 ± 10 b: 68 ± 10	27.9 ± 3.3	a: 27 ± 3.8 b: 29 ± 3.6	NR	a: Anterior b: Anterolateral	Pre-op, 6 weeks, 3 mo	22
McCrory *et al.* 2001[66]	Case control		✓	27	35	59.7 ± 13.8	27.5 ± 5.7	NR	NR	Not specified	10.5 mo	16
Meneghini *et al.* 2008[67]	Case series	✓		a: 8 b: 8 c: 7	N/A	a: 54 ± 9 b: 54 ± 9 c: 54 ± 9	N/A	a: 26 ± 2.3 b: 26 ± 2.3 c: 26 ± 2.3	N/A	a: Two incision (anterior and buttock) b: Posterior (mini incision) c: Anterolateral (mini incision)	Pre-op, 6 wk	20
Miki *et al.* 2004[68]	Case series	✓		17	N/A	52.6 (SD NR)	N/A	NR	N/A	Posterior	Pre-op, 1 mo, 3 mo, 6 mo, 12 mo	20
Muller *et al.* 2012[69]	Case series	✓		a: 15 b: 15	N/A	a: 64.3 ± 7 b: 66.2 ± 8	N/A	a: 26.9 ± 3.3 b: 27 ± 3.1	N/A	a: Anterolateral b: Direct lateral	Pre-op, 3 mo	22
Nankaku *et al.* 2012[70]	Case control		✓	18	18	47.7 ± 10	47.4 ± 15.3	20.4 ± 2.1	20.8 ± 1.9	Direct lateral (Dall's)	4 weeks	18

Nankaku *et al.* 2007[71]	Case control		✓	15	14	47 ± 10.2	46 ± 13.2	20.3 ± 2.2	20.7 ± 1.9	Anterolateral (Dall's)	4 weeks	20
Nantel *et al.* 2009[72]	Case control		✓	10	10	49 ± 7.5	48.6 ± 6	29.9 ± 6.6	26.4 v 3.4	Posterior	6 weeks	21
Perron *et al.* 2000[73]	Case control		✓	18	15	65.6 ± 6	65.5 ± 6.5	NR	NR	Posterior & anterolateral≠	10.7 mo	17
Queen *et al.* 2011[10]	Case series	✓		a: 8 b: 12 c: 15	N/A	a: 58 ± 7 b: 55.3 ± 8.2 c: 55.4 ± 10.9	N/A	a: NR b: NR c: NR	N/A	a: Lateral b: Posterior c: Anterolateral	Pre-op, 6 weeks	20
Queen *et al.* 2013[74]	Case series	✓		a: 10 b: 10 c: 10	N/A	a: 60 ± 6.5 b: 57 ± 6.2 c: 57.6 ± 11.2	N/A	a: NR b: NR c: NR	N/A	a: Lateral b: Posterior c: Anterolateral	Pre-op, 6 weeks, 12 mo	19
Rathod *et al.* 2014[75]	Case series	✓		a: 11 b: 11	N/A	a: 58 ± 6.7 b: 61.8 ± 9.1	N/A	a: 25.9 ± 2.2 b: 25.43 ± 3	N/A	a: Anterior b: Posterior	Pre-op, 6 mo, 12 mo	24
Reininga *et al.* 2013[76]	Prospective cohort	✓	✓	40	30	60.5 ± 9.5	65.8 ± 6	26.2 ± 3.5	23.9 ± 3.2	Posterior	Pre-op, 6 weeks, 3 mo, 6 mo	23
Rosenberg 1982[77]	Case control		✓	10	10	66.4 ± 6.9	64.9 ± 4.8	NR	NR	Anterolateral	>12mo	15
Rosler and Perka 2000[78]	Prospective cohort	✓	✓	26	10	64.6 ± 7.7	42.1 ± 13.5	NR	NR	Lateral	Pre-op, 14.4 wk, 27.8 wk	13
Shrader *et al.* 2009[79]	Prospective cohort	✓	✓	7	7	51.9 ± 10.1	50.4 ± 8.2	NR	NR	Posterolateral	Pre-op, 3 mo	20
Sicard-Rosenbaum *et al.* 2002[11]	Case control		✓	15	30	59.9 ± 14.9	60.2 ± 15	NR	NR	Not specified	23.6 mo	14
Stansfield and Nicol 2002[80]	Case control		✓	5	M = 5; F = 6	52.6 ± 6.6	M = 49.4 ± 5; F = 49.7 ± 5.2	NR	M = NR; F = NR	Not specified	18.6 mo	11
Talis *et al.* 2008[81]	Case control		✓	27	27	56 ± 10	55 ± 9	NR	NR	Not specified	19 mo	17
Tanaka *et al.* 2010[82]	Prospective cohort	✓	✓	43	26	59.7 ± 7.9	61.3 ± 11.4	NR	NR	Posterolateral	Pre-op, 2 mo, 6 mo, 12 mo	20
Tateuchi *et al.* 2011[83]	Case control		✓	12	12	63.2 ± 7.2	63.4 ± 5.1	22.5 ± 3.3	21.6 ± 2.1	Not specified	>6 mo	18
van den Akker-Scheek *et al.* 2007[84]	Prospective cohort	✓	✓	63	19	62 ± 12.6	61.7 ± 9.4	26.4 ± 3.3	24.9 ± 2.3	Not specified	Pre-op, 6 weeks, 6 mo	19
Varin *et al.* 2013[85]	Case control		✓	a: 20 b: 20	20	a: 66.2 ± 6.7 b: 60.5 ± 6	63.5 ± 9.4	a: 27.2 ± 5 b: 28.5 ± 4.9	24.9 ± 3.5	a: Lateral b: Anterior	10.6 mo 9.6 mo	20
Vogt *et al.* 2004[86]	Case control		✓	14	10	63 ± 4	61 ± 6	NR	NR	Posterolateral	6 weeks	13
Vogt *et al.* 2003[87]	Case control		✓	12	10	61.5 ± 6.7	59.5 ± 6.1	NR	NR	Not specified	6 weeks	16
Waldman and Foucher 2012[88]	Case series	✓		132	N/A	60.5 ± 10	N/A	28.5 ± 4	N/A	Not specified	Pre-op, 12 mo	8
Ward *et al.* 2008[89]	Case series	✓		a: 11 b: 10 c: 18 d: 30	N/A	a: 55 ± 2 b: 64 ± 2 c: 61 ± 2 d: 64 ± 1	N/A	a: 28.9 ± 1.2 b: 27.8 ± 1.1 c: 29.8 ± 1 d: 26.1 ± 0.5	N/A	a: Anterolateral (mini incision) b: Anterolateral (Judet mini incision) c: Posterior d: Posterior (mini incision)	Pre-op, 6 weeks, 6 mo	14
Wesseling *et al.* 2016[90]	Case control		✓	12	18	47.75 ± 13.2	53 ± 5	25.52 ± 3	23.67 ± 3	Anterior	12 mo	17
Whatling *et al.* 2008[91]	Prospective cohort	✓	✓	a: 14 b: 13	16	a: 64.21 ± 10.9 b: 60.46 ± 11.5	46.25 ± 7.4	a: NR b: NR	NR	a: Direct lateral b: Posterior	Not stated	10
Wimmer *et al.* 2012[92]	Prospective cohort	✓	✓	a: 10 b: 12 c: 7	23	a: 59 ± 7.3 b: 55.7 ± 9.9 c: 57 ± 11.8	53.8 ± 6.5	a: 26.7 ± 2.2 b: 28.9 ± 3.8 c: 30.7 ± 6.6	26.1 ± 4.9	a: Two incision (anterior and buttock) b: Anterolateral (mini incision) c: Posterolateral (mini incision)	6 weeks, 3 mo	16

≠ Surgical approaches combined; *Missing gait data where authors were contacted; SD, standard deviation; RCT, randomised controlled trial; NR, not reported; N/A, not applicable; mo, months; wk, week; y, year.

Table II
Summary of findings for gait parameters across each time point. Change from pre-operative to post-operative and comparison of post-operative THA patients to healthy individuals

Pre-operative vs post-operative

Follow-up time points and variables	Study groups (n=)	I^2, %	SMD (95% CI)	Strength of evidence*
6 weeks				
Velocity	20	70	0.32 (0.14–0.50)	Moderate
Single limb support time	5	36	0.44 (0.19–0.69)	Moderate
Double limb support time	3	50	−0.03 (−0.46 to 0.40)	Moderate
Stride length	11	87	0.40 (0.19–0.61)	Moderate
Stride time	3	70	0.04 (−0.13 to 0.20)	Moderate
Step width	5	66	0.05 (−0.25 to 0.35)	Strong
Step length	10	75	0.41 (0.23–0.59)	Moderate
Hip flexion/extension ROM	4	88	0.49 (−0.29 to 1.27)	Moderate
Hip abduction/adduction ROM	4	39	0.33 (−0.19 to 0.86)	Strong
Hip internal/external ROM	4	9	0.36 (0.05–0.67)	Strong
3 months				
Velocity	17	63	0.78 (0.57–0.99)	Moderate
Single limb support time	5	28	0.59 (0.35–0.82)	Strong
Stride length	7	51	0.63 (0.38–0.88)	Moderate
Stride time	3	60	−0.38 (−0.68 to −0.07)	Moderate
Step width	8	90	0.02 (−0.63 to 0.66)	Moderate
Step length	7	31	0.52 (0.33–0.71)	Strong
Hip flexion/extension ROM	4	80	1.07 (0.31–1.84)	Moderate
Hip abduction/adduction ROM	5	95	1.03 (0.24–1.82)	Moderate
Hip internal/external ROM	4	89	0.50 (0.01–1.00)	Moderate
Peak hip flexion angle	3	86	0.16 (−0.47 to 0.78)	Moderate
Peak hip abduction angle	2	0	−0.39 (−0.62 to −0.16)	Moderate
6 months				
Velocity	9	32	1.01 (0.81–1.21)	Strong
Step length	6	75	0.90 (0.50–1.31)	Moderate
Cadence	6	96	−0.08 (−1.05 to 0.89)	Moderate
Stance phase	3	34	−0.14 (−0.42 to 0.13)	Limited
Pelvic obliquity ROM	4	98	−0.81 (−2.60 to 0.99)	Moderate
12 months				
Velocity	11	78	1.28 (1.01–1.56)	Moderate
Hip abduction/adduction ROM	4	39	0.33 (−0.19 to 0.86)	Strong
Hip internal/external ROM	4	9	0.36 (0.05–0.67)	Strong

Post-operative THA patients vs healthy individuals

Follow-up time points and variables	Study groups (n=)	I^2, %	SMD (95% CI)	Strength of evidence*
6 weeks				
Velocity	13	69	−1.81 (−2.22 to −1.40)	Moderate
Single limb support time	6	79	−0.72 (−1.38 to −0.05)	Moderate
Double limb support time	3	91	2.22 (0.26–4.19)	Moderate
Stride length	8	61	−1.90 (−2.43 to −1.37)	Moderate
Step width	5	0	1.33 (0.91–1.75)	Strong
Step length	2	49	−1.36 (−1.90 to −0.83)	Moderate
Hip flexion/extension ROM	4	0	−2.59 (−3.11 to −2.06)	Moderate
Hip abduction/adduction ROM	4	44	−1.76 (−2.36 to −1.15)	Moderate
Hip internal/external ROM	4	13	0.18 (−0.23 to 0.59)	Moderate
3 months				
Velocity	10	82	−1.22 (−1.83 to −0.61)	Moderate
Single limb support time	4	78	−0.73 (−1.59 to 0.12)	Moderate
Double limb support time	5	97	−0.28 (−2.05 to 1.58)	Moderate
Stride length	6	80	−1.60 (−2.45 to −0.74)	Moderate
Step width	8	94	1.90 (0.60–3.20)	Moderate
Step length	3	0	−0.88 (−0.68 to −0.01)	Moderate
Swing time	3	0	−0.39 (−0.67 to −0.11)	Strong
Hip flexion/extension ROM	5	56	−1.88 (−2.47 to −1.28)	Strong
Hip abduction/adduction ROM	4	0	−1.41 (−1.83 to −0.99)	Strong
Hip internal/external ROM	4	79	0.26 (−0.60 to 1.11)	Moderate
Pelvis obliquity ROM	3	99	−0.20 (−3.31 to 2.90)	Moderate
Peak pelvis obliquity angle	4	96	−0.24 (−1.83 to 1.34)	Moderate
Minimum pelvis obliquity angle	4	96	−0.41 (−1.96 to 1.13)	Moderate
Peak hip abduction moment	4	21	0.02 (−0.44 to 0.49)	Moderate
6 months				
Velocity	8	64	−0.69 (−1.10 to −0.29)	Moderate
Single limb support time	5	82	−0.33 (−1.08 to 0.42)	Moderate
Double limb support time	7	88	0.18 (−0.51 to 0.88)	Moderate
Stride length	7	0	−0.78 (−1.06 to −0.49)	Strong
Step length	4	51	−0.35 (−0.68 to −0.01)	Strong
Swing time	5	75	0.36 (−0.14 to 0.86)	Moderate
Hip flexion/extension ROM	3	0	−1.33 (−1.83 to −0.82)	Strong
Pelvis obliquity ROM	5	95	0.28 (−1.02 to 1.57)	Moderate
12 months				
Velocity	7	77	−0.59 (−1.08 to −0.11)	Moderate
Single limb support time	2	0	−0.82 (−1.23 to −0.41)	Moderate
Double limb support time	3	59	−0.38 (−0.83 to 0.08)	Moderate
Stride length	3	0	−1.27 (−1.63 to −0.91)	Moderate
Step length	3	90	−0.54 (−1.46 to 0.38)	Moderate
Hip flexion/extension ROM	3	65	−1.16 (−1.83 to −0.49)	Strong
Peak hip extension angle	4	97	0.11 (−1.68 to 1.91)	Moderate
Pelvis obliquity ROM	4	78	0.09 (−0.47 to 0.65)	Moderate
Pelvis flexion/extension ROM	5	73	0.48 (0.00–0.96)	Moderate
24 months				
Velocity	2	0	−0.57 (−0.98 to −0.15)	Limited

* Strength of evidence was determined as per Van Tulder *et al.* 2003[50].

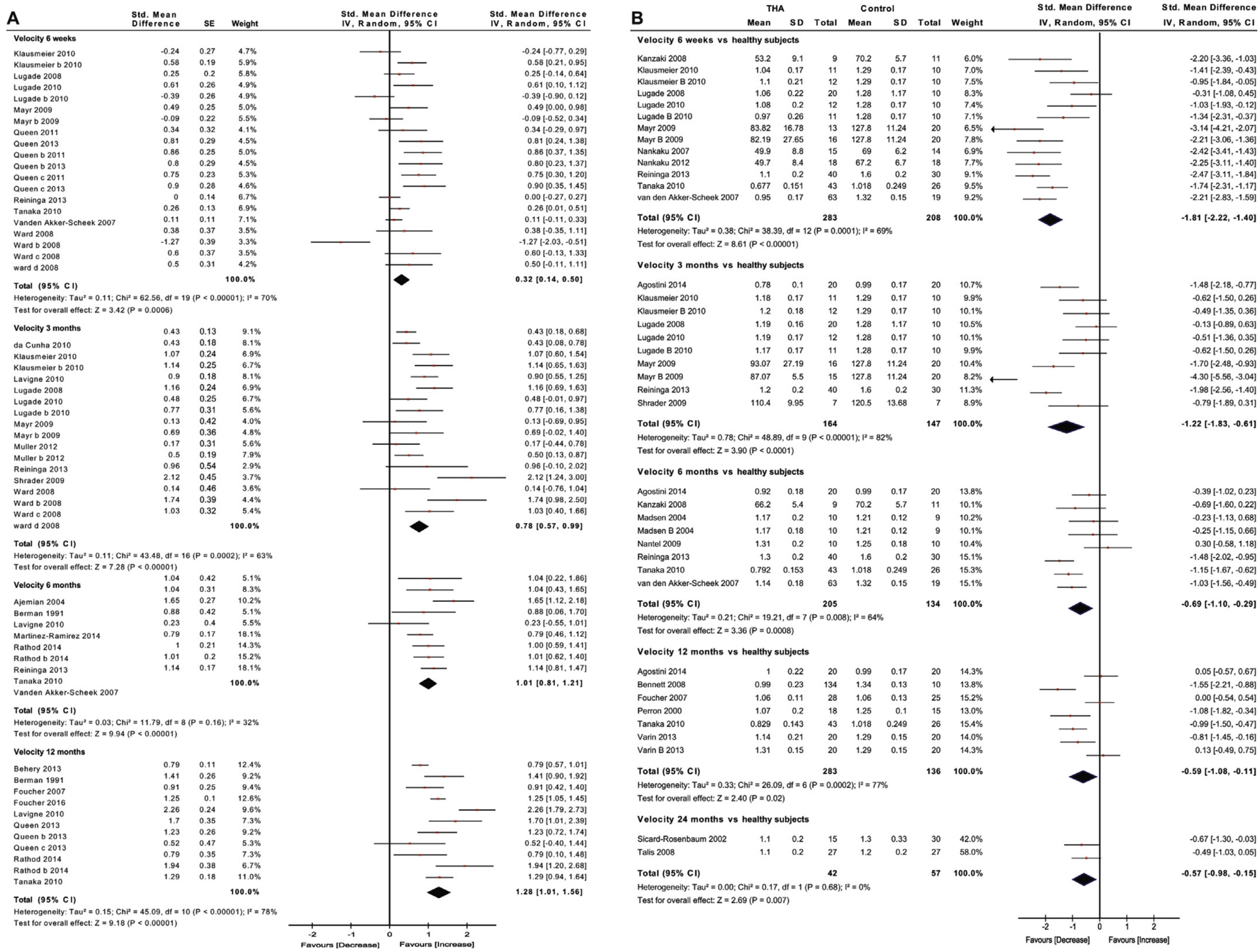

Fig. 2. A (left) illustrates the change in walking speed following THA compared to the pre-operative status. B (right) compares post-operative THA patients to healthy individuals. Studies listed as (Author) a, b, c represent different surgical approaches used and reported in the study.

Three studies provided moderate evidence for a very large increase in double support time at 6 weeks (SMD: 2.22, $P < 0.03$), however, patients were comparable to healthy individuals at 3 months (SMD: −0.28, $P = 0.77$), 6 months (SMD: 0.18, $P = 0.60$), and 12 months (SMD: −0.38, $P = 0.10$). Large increases in step width compared to healthy controls were evident at 6 weeks (SMD: 1.33, $P < 0.001$) and 3 months (SMD: 1.90, $P = 0.004$).

Kinematic: comparison to pre-operative level

Moderate evidence from four studies demonstrated small changes in sagittal plane hip ROM compared to pre-operative level at 6 weeks (SMD: 0.49, $P = 0.22$), with a moderate increase at 3 months (SMD: 1.07, $P = 0.006$) [Fig. 4(A)]. There was no change in coronal plane hip ROM at 6 weeks (SMD: 0.33, $P = 0.22$) and 12 months (SMD: 0.33, $P = 0.22$), with moderate evidence of a significant increase at 3 months (SMD: 1.03, $P = 0.01$) [Fig. 5(A)]. Pooled results indicated a small increase in transverse plane hip ROM at 6 weeks (SMD: 0.36, $P = 0.02$), 3 months (SMD: 0.50; $P = 0.05$) and 12 months (SMD: 0.36, $P = 0.02$) (Supplementary File 3). Two studies provided moderate evidence of a small decrease in peak hip abduction angle at 3 months (SMD: −0.39, $P < 0.001$). Moderate evidence indicated no significant change in peak hip flexion at 3 months (SMD: 0.16, $P = 0.63$) and coronal plane pelvic obliquity angle at 6 months (SMD: −0.81, $P = 0.38$) (Supplementary File 3).

Kinematic: comparison to controls

Very large deficits in sagittal plane hip ROM compared to healthy individuals were observed at 6 weeks (SMD: −2.59, $P < 0.001$), decreasing in magnitude but persisting at 3 months (SMD: −1.88, $P < 0.001$), 6 months (SMD: −1.33, $P < 0.001$) and 12 months (SMD: −1.16, $P < 0.001$) [Fig. 4(B)]. This also occurred for coronal plane hip ROM, with large deficits at 6 weeks (SMD: −1.76, $P < 0.001$) and 3 months (SMD: −1.41, $P < 0.001$) [Fig. 5(B)]. There were negligible changes in transverse plane hip ROM compared to healthy individuals at 6 weeks (SMD: 0.18, $P = 0.39$) and 3 months (SMD: 0.26, $P = 0.56$).

Moderate evidence from five studies demonstrated a significant increase in sagittal plane pelvis ROM compared to healthy individuals with a small effect at 12 months (SMD: 0.48, $P = 0.05$). THA patients were comparable to healthy individuals for coronal plane pelvic obliquity angle at 3 months (SMD: −0.20, $P = 0.90$), 6 months (SMD: 0.28, $P = 0.67$), and 12 months (SMD: 0.09, $P = 0.75$) (Supplementary File 3).

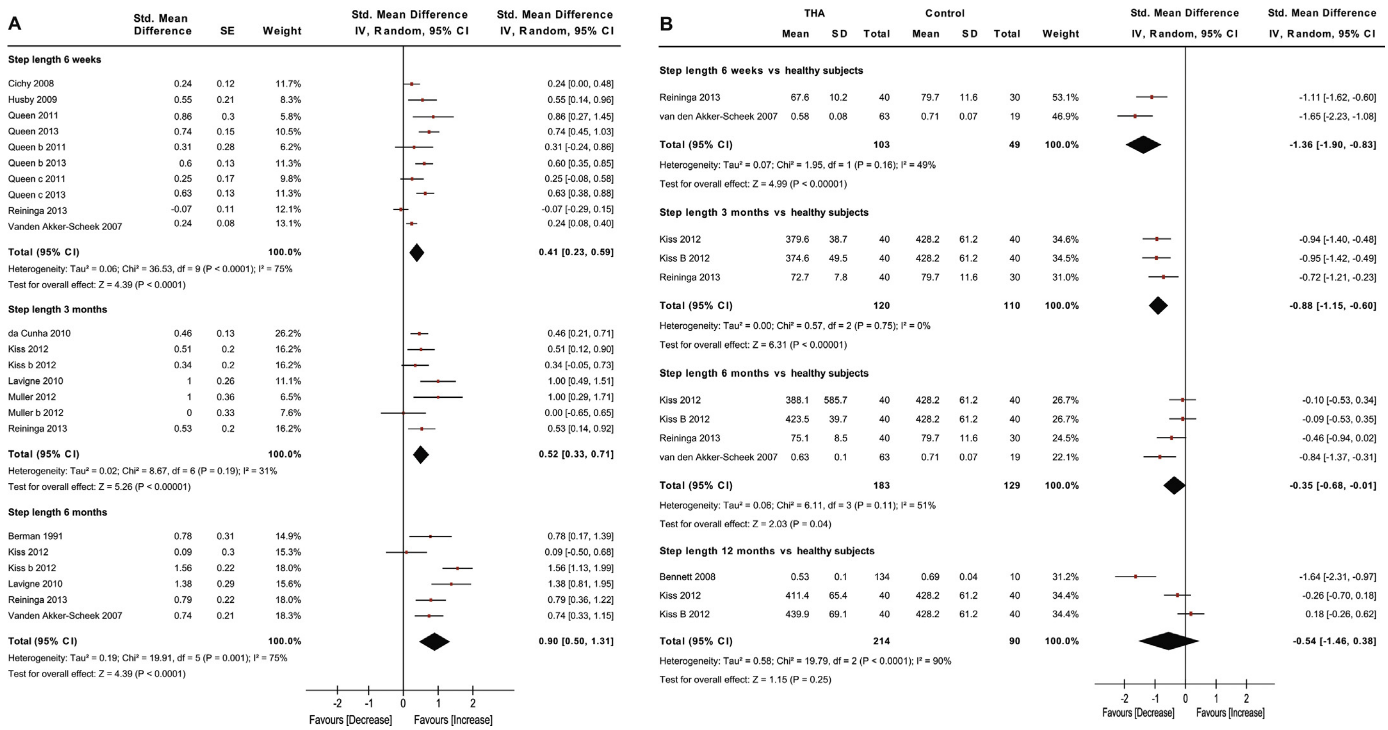

Fig. 3. A (left) illustrates the change in step length following THA compared to the pre-operative status. B (right) compares post-operative THA patients to healthy individuals. Studies listed as (Author) a, b, c represent different surgical approaches used and reported in the study.

Kinetic: comparison to controls

Four studies provided moderate evidence demonstrating THA patients were comparable to healthy individuals for peak hip abduction moment at 3 months (SMD: 0.02, $P = 0.92$). There was insufficient data to compare the change from pre-operative status.

Meta-regression and sensitivity analysis

Pooled analyses for velocity (6 weeks, 3 and 12 months), as well as step length and stride length (6 weeks), indicated high statistical heterogeneity ($P < 0.05$) with greater than 10 studies reporting data at each time point. Among these factors, there was an association with the velocity effect size and younger age at 3 months and 12 months. There was an association between step length effect size and study sample size at 6 weeks. No association was found for BMI, anterior surgical approach, gender or risk of bias score (Table III). The sensitivity analysis revealed no change in the magnitude of the overall effect and the level of significance when the correlation estimates were zero (Supplementary file 5).

Risk of publication bias

Egger's regression test demonstrated no evidence of publication bias for velocity at 6 weeks ($\beta = 1.04$, $P = 0.368$), 3 months ($\beta = 1.6$, $P = 0.144$), and 12 months ($\beta = 1.4$, $P = 0.361$) or for stride and step length at 6 weeks ($\beta = 2.00$, $P = 0.657$; $\beta = 2.46$, $P = 0.187$, respectively).

Risk of methodological bias

Inter-rater agreement for risk of bias scoring was high ($\kappa = 0.77$). Of a possible maximum 26 points, the mean risk of bias score across studies was 18, SD = 4 (range = 7 to 24). Inadequate reporting of the sampling methods for recruitment (item 4), post-operative rehabilitation protocol (item 9), and number and characteristics of patients lost to follow-up (item 19) was common. Full risk of bias scoring is provided in Supplementary File 4.

Discussion

The aims of this systematic review were to determine the change in gait biomechanics after THA compared to the pre-operative gait status; and to compare the recovery of gait following THA with healthy individuals. This review identified evidence for moderate to large pre to post-operative changes from 6 weeks to 12 months in spatiotemporal and kinematic parameters. Compared to healthy individuals, although selected gait parameters appeared to normalise after THA, residual deficits in walking speed, stride length and sagittal plane hip ROM existed at 12 months postoperative.

Relatively consistent improvements were demonstrated over time in walking velocity, step length and stride length following THA compared to pre-operative levels. The observed changes in gait velocity following surgery in this meta-analysis did not meet the meaningful clinically important improvements in gait velocity stated by Foucher *et al.* (2016)[39]. Early improvements after THA were evident for walking speed, step length, stride length, and single-limb support time at 6 weeks, with improvements relative to before surgery demonstrated up to 12 months. Despite these observed improvements in spatiotemporal parameters compared to the pre-operative status, patients were only comparable to healthy individuals for step length, which demonstrated early recovery and return to normal function from 6 weeks post-surgery. Importantly, despite early changes and significant improvements in walking speed for up to 12 months post-surgery, lower walking speed is still present at 12 months compared to healthy individuals. Step width was wider compared to healthy individuals at 6 weeks

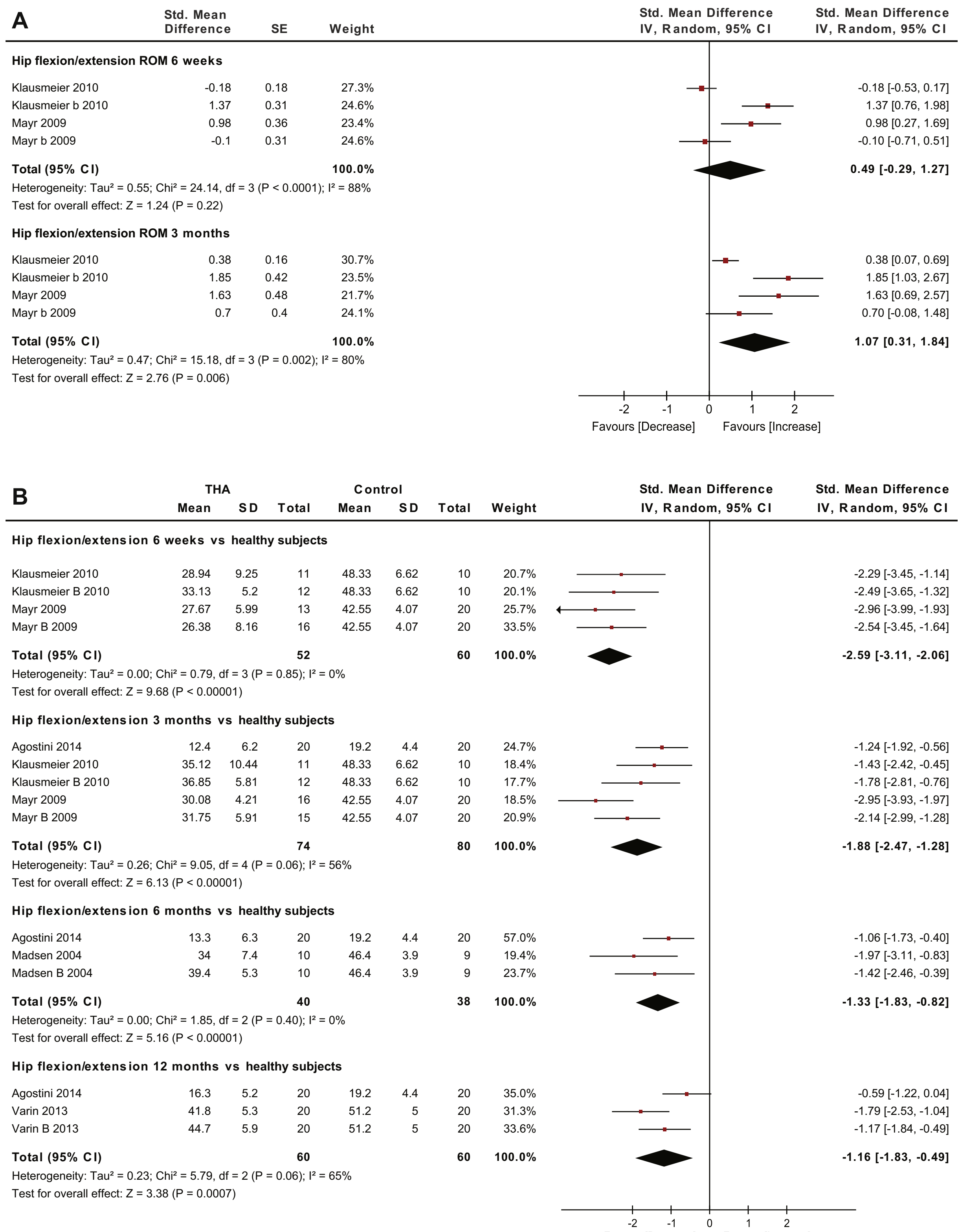

Fig. 4. A (top) illustrates the change in sagittal plane hip flexion/extension ROM following THA compared to the pre-operative status. B (bottom) compares post-operative THA patients to healthy individuals. Studies listed as (Author) a, b, c represent different surgical approaches used and reported in the study.

and 3 months indicating patients continue to demonstrate a wider based of support during gait after surgery.

The kinematic data revealed increases in sagittal plane hip ROM and transverse plane hip ROM compared to pre-operative function at 6 weeks and up to 12 months. Despite continuous improvements following THA for sagittal plane hip ROM, reduced hip ROM in THA patients compared to healthy individuals at 12 months was evident. This may be due to an increase in pelvis and/or trunk flexion

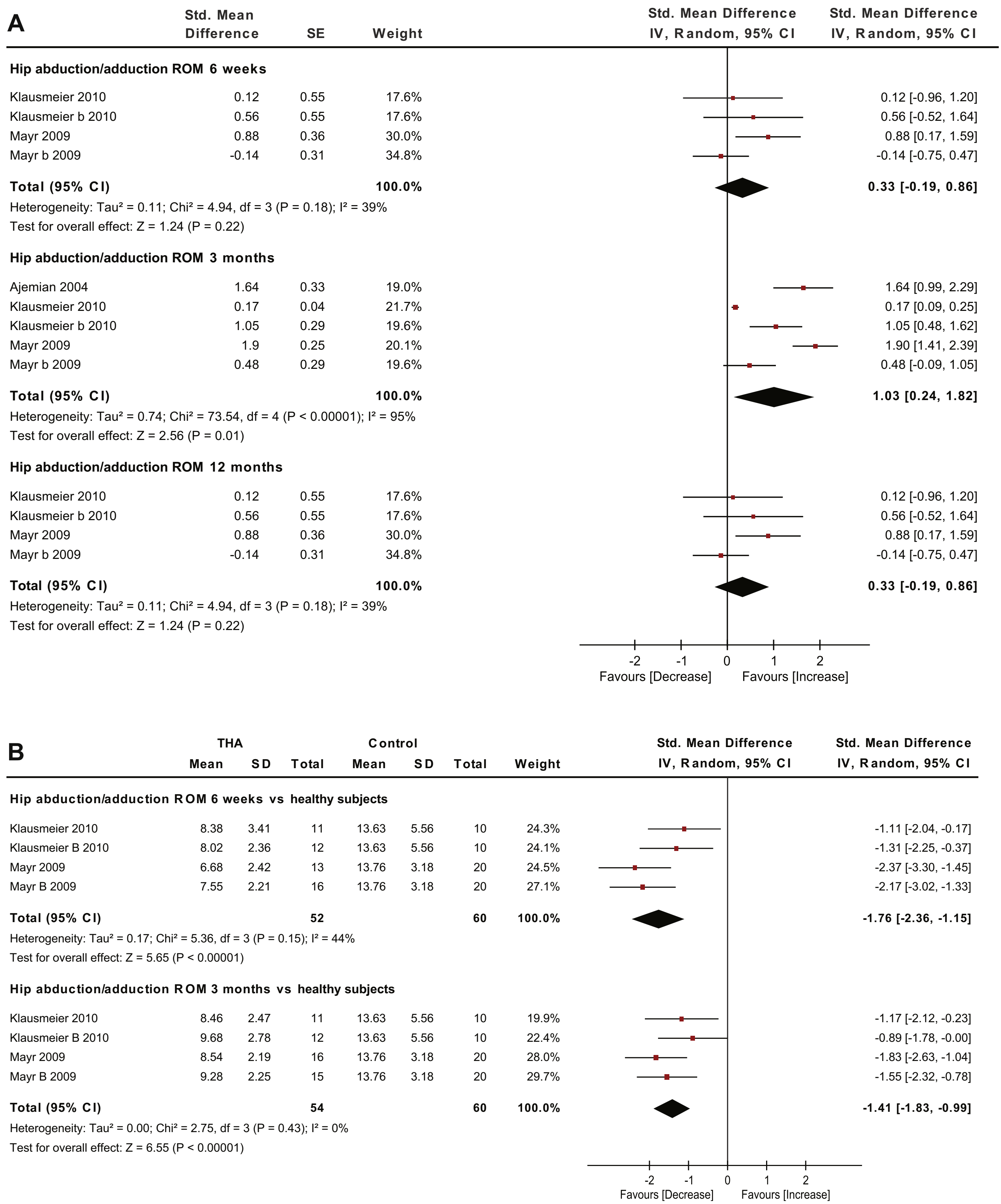

Fig. 5. A (top) illustrates the change in coronal plane hip abduction/adduction ROM following THA compared to the pre-operative status. B (bottom) compares post-operative THA patients to healthy individuals. Studies listed as (Author) a, b, c represent different surgical approaches used and reported in the study.

developed as a strategy to avoid pain before surgery[65], and potentially maintained following THA[5]. Coronal plane hip abduction/adduction revealed no significant change from pre-operative status up to 12 months post THA, with a significantly lower coronal plane hip ROM compared to healthy individuals. Abnormal coronal plane hip kinematics following THA could be due to several reasons including muscle weakness in the affected limb due to pain and impaired function before surgery[94], and incision of the

Table III
Meta regression analysis of factors potentially related to heterogeneity

	Velocity 6 weeks		Velocity 3 months		Velocity 12 months		Step length 6 weeks		Stride length 6 weeks	
	β (95% CI)	*P* Value	β (95% CI)	*P* Value	β (95% CI)	*P* Value	β (95% CI)	*P* Value	β (95% CI)	*P* Value
Age	−0.25 (−0.77 to 0.27)	.324	−.052 (−.102 to −.001)	**.046**	−.094 (−.185 to −.003)	**.045**	−.029 (−.107 to .048)	.406	−.021 (−.086 to .044)	.484
BMI	−.002 (−.106 to .102)	.968	.055 (−.093 to .204)	.437	.011 (−.867 to .889)	.970	.255 (−1.244 to 1.755)	.275	−.012 (−.433 to .409)	.932
Sample size	−008 (−0.20 to .005)	.217	−.005 (−.019 to .010)	.508	−.002 (−.010 to .006)	.583	−.011 (−.020 to −.001)	**.033**	−.034 (−.112 to .045)	.354
Surgical Approach*	.195 (−.315 to .705)	.431	.224 (−.532 to .981)	.537	.725 (−.477 to 1.927)	.206	–	–	.354 (−.290 to .998)	.245
% females	.003 (−.007 to .014)	.497	−.005 (−.017 to .007)	.386	−.006 (−.037 to .025)	.645	−.016 (−.040 to .008)	.141	.011 (−.012 to .034)	.271
Risk of bias	−.047 (−.105 to .011)	.107	−.062 (−.131 to .007)	.073	.051 (−.042 to .144)	.246	−.041 (−.132 to .050)	.326	−.095 (−.254 to .064)	.210

Bold indicates covariates associated at a *P* value <0.05.
* Comparison of the gluteal muscle sparing (anterior) approach to the more conventional posterior and lateral surgical approaches.

abductor muscles during surgery[65]. Pelvic obliquity ROM was comparable to healthy individuals from 3 months and maintained up to 12 months.

A meta-regression was performed to identify possible explanations for the observed heterogeneity in the gait parameters of velocity, stride length and step length. Only age was associated with effect size of walking speed at 3 months and 12 months post-operatively, indicating younger patients were associated with earlier recovery. The study sample size was related to effect size heterogeneity for step length at 6 weeks, with larger sample sizes showing a smaller effect for increased step length compared to pre-operative gait.

Despite previous systematic reviews describing the deficient gait parameters in patients following THA compared to healthy individuals[7,8] the pre-operative gait was not considered to determine the trend in recovery. This meta-analysis has for the first time, concurrently mapped the recovery in gait biomechanics after THA and compared postoperative status to healthy controls up to 2 years after surgery. A greater number of longitudinal cohort studies with follow-up beyond 12 months are required to appropriately map the trajectory of recovery after THA and determine the effect of surgery on gait function in the long term. Furthermore, greater consistency of reporting of gait parameters would facilitate easier comparison across studies, particularly for kinetic gait parameters. Unfortunately inconsistency in reporting precluded meta-analysis of most joint moment parameters. A greater understanding the effect of THA on muscle function in future studies will shed light onto the mechanisms underlying the deficits in gait biomechanics identified in this review.

Certain limitations of this review should be acknowledged. First, all study designs were included in the review to determine the changes in gait biomechanics following THA and compared to healthy individuals. Therefore, this review is susceptible to bias through the inclusion of lower level study designs. However, we undertook an established grading of evidence that considers study risk of bias, magnitude of the effect size and heterogeneity to synthesise the findings. Second, the studies included to evaluate the change in gait from pre-to post-operative status were not synonymous with the studies included to compare post-operative gait to healthy individuals due to the limited number of longitudinal studies that included a control group. Therefore, direct comparison between the two separate analyses is cautioned. Some of the meta-analyses were based on a smaller number of studies of varying methodological quality, although the regression analyses indicated the risk of bias scores could not explain any observed heterogeneity. Finally, only studies published in English were included due to limited translation resources. Therefore it is uncertain if inclusion of non-English studies would alter the outcomes of the review.

Conclusion

Compared with OA patients before surgery THA was successful in improving walking speed, step, stride length, single-limb support time, sagittal and coronal plane hip ROM. Despite these observed improvements from pre-operative OA individuals, patients continued to demonstrate deficiencies compared to healthy individuals for walking speed, stride length, single limb support time and sagittal plane hip ROM at 12 months. Improved understanding of the trajectories of recovery in gait function after THA may assist in managing expectations for both patients and clinicians, with further research required to elucidate the impact of these impairments and relationships with clinical outcome.

Contributions

JSB & JA were responsible for the conception and design of the research, reviewing articles, analysing data, interpreting the results of the review, writing and drafting the manuscript, and approving the final version of the manuscript. MJN was responsible for performing the review, interpreting results of the research and revising the manuscript. MT was responsible for conception and design of the review, interpreting the results, and revision of the manuscript for important intellectual content. JK was responsible for interpreting the results of the review and revision of the article for important intellectual content. LBS and DT were responsible for conception and design of the review, interpreting the results of the review, revision of the article for important intellectual content. All authors read and approved the final version of the manuscript.

Conflicts of interest

The authors do not have any significant conflicts of interest relevant to this manuscript.

Role of the funding source

None of the funding sources had input into the study design, analysis and interpretation of data; in the writing of the manuscript; and in the decision to submit the manuscript for publication.

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Supplementary data

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