EFORT open reviews

Temporal subsidence patterns of cemented polished taper-slip stems: a systematic review

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- The literature was reviewed to establish the levels of stem subsidence for both double and triple-tapered implants in order to determine whether there were any differences in subsidence levels with regard to the methods of measurement, the magnitude and rate of subsidence and clinical outcomes.

- All studies reporting subsidence of polished taper-slip stems were identified. Patient demographics, implant design, radiological findings, details of surgical technique, methods of measurement and levels of subsidence were collected to investigate which factors were related to increased subsidence.

- Following application of inclusion and exclusion criteria, 28 papers of relevance were identified. The studies initially recruited 3090 hips with 2099 being available for radiological analysis at final follow-up. Patient age averaged 68 years (42–70), 60.4% were female and the average body mass index (BMI) was 27.4 kg/m^2 (24.1–29.2).

- Mean subsidence at one, two, five and 10 years was 0.97 mm, 1.07 mm, 1.47 mm and 1.61 mm respectively. Although double-tapered stems subsided more than triple-tapered stems at all time points this was not statistically significant ($p > 0.05$), nor was the method of measurement used ($p > 0.05$).

- We report the levels of subsidence at which clinical outcomes and survivorship remain excellent, but based on the literature it was not possible to determine a threshold of subsidence beyond which failure was more likely.

- There were relatively few studies of triple-tapered stems, but given that there were no statistically significant differences, the levels presented in this review can be applied to both double and triple-tapered designs.

Keywords: cemented femur; subsidence; taper-slip stems

Introduction

Total hip replacement is a safe, reliable and effective treatment for end-stage arthritis and has been hailed as 'the operation of the century'.[1] Sir John Charnley is credited with the creation of the 'modern' total hip replacement, and his low-friction arthroplasty produced excellent long-term results.[2] The original polished, cemented flatback stem functioned as a taper[3,4] but subsequent changes to the design changed it into a composite beam.[5]

Taper-slip, or force-closed, cemented polished femoral implants are designed to subside within the cement mantle in order to distribute load in a more physiological fashion.[6] This differs to the composite beam, or shape-closed designs, where fixation is required at all interfaces and subsidence signifies loosening.[7] The modern taper-slip stems now dominate the cemented hip market in the United Kingdom, with both double and triple-tapered designs available, but despite their popularity and increasingly widespread use, the magnitude and duration of subsidence have not yet been fully established.[8,9]

The literature on the subsidence of polished taper-slip stems at different time intervals was reviewed in order to establish the levels compatible with excellent long-term survivorship, as well as any differences between double and triple-tapered designs, or the methods used to measure the subsidence.

Methods

Search strategy and criteria

Embase, MEDLINE and CINAHL databases were searched for all relevant articles from their inception until October 2020 (search strategies are presented in Table 1). The searches were performed in duplicate by two authors (KB and DHS). Citations within the selected articles, were also examined for their relevance. All articles meeting the inclusion criteria were evaluated.

Table 1. Search strategies

Database	Search terms
CINAHL	"(stem subsidence polished taper-slip stem).ti,ab OR (stem subsidence polished taper slip stem).ti,ab OR (stem subsidence polished force-closed stem).ti,ab OR (stem subsidence polished force closed stem).ti,ab OR (stem subsidence polished tapered stem).ti,ab OR (stem subsidence polished cemented stem).ti,ab"
MEDLINE	"(subsidence polished taper-slip stem).ti,ab OR (subsidence polished taper slip stem).ti,ab OR (subsidence polished force-closed stem).ti,ab OR (subsidence polished force closed stem).ti,ab OR (subsidence polished cemented stem).ti,ab OR (subsidence polished tapered stem).ti,ab"
Embase	"(subsidence polished force-closed stem).ti,ab OR (subsidence polished force closed stem).ti,ab OR (subsidence polished taper-slip stem).ti,ab OR (subsidence polished taper slip stem).ti,ab OR (subsidence polished tapered stem).ti,ab OR (subsidence polished cemented stem).ti,ab"

The inclusion criteria were papers which included patients undergoing primary cemented total hip replacement, using a polished, force-closed or taper-slip stem and quoting a value for subsidence. Exclusion criteria included any papers not meeting the inclusion criteria, papers unavailable in English, prostheses not in clinical use, collared prostheses, and abstracts. Eligible studies were randomized and non-randomized controlled trials, cohort or case-control studies and case series.

If there was more than one paper reporting on the same patient cohort, the earlier one was removed, but the subsidence result retained to calculate average annual subsidence rates. Where there was disagreement between authors, resolution was achieved with discussion; however, where discussion did not result in consensus, the senior author (DHS) was final arbiter. After applying the inclusion and exclusion criteria, 28 papers were selected.

Data collection and analysis

The review was performed in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidance.[10] All search results had full title and abstract reviewed. Inclusion and exclusion criteria were then applied, and agreement confirmed by two authors (KB and DHS). Those whose abstracts met the inclusion criteria then had the full article reviewed and those found to be relevant were included in this review (Fig. 1).

Demographic data were collected including age, gender, body mass index (BMI), pre-operative diagnosis, duration of follow-up, the number of hips enrolled and the number available for final radiological review. Clinical data included implant type, stem geometry, surgical approach, cement and cementing technique, Oxford (OHS),[11] and Harris Hip Scores (HHS),[12] and survivorship. Radiological data included the method of radiographic analysis, Barrack grading of the cement mantle,[13] distal femoral cortical hypertrophy, direction of migration and subsidence.

Data were extracted from the papers by systematic analysis of each article and summarization in Microsoft Excel version 2013 (Microsoft, Redmond, WA, USA).

Quality appraisal

An assessment of the quality of the papers was performed using the National Heart, Lung, and Blood Institute (NIH) Quality assessment tools[14] by two authors (KB and DHS). Each study was rated good, fair or poor and where there were disagreements in rating, these were resolved through discussion with a consensus being reached in each case.

Statistical analysis

Statistical analysis was performed using SAS software (SAS, Marlow, Buckinghamshire, UK). Each study outcome was weighted by the number of patients in that study to assign higher weights to more precise mean estimates and vice versa. Studies that were assigned larger weights were more influential in determining the parameter estimates compared to studies that had smaller weights. The normality of the response variable was assessed via QQ plots, with a view to determine whether log transformation of the data was required. The statistical analyses involved a range of tests specific for continuous response variables including independent sample t-tests and Analysis of Variance.

Results

Study characteristics

After application of the inclusion and exclusion criteria, 28 papers were selected.[8,15–41] In total, 3090 hips were originally recruited to the studies, with 2099 being available for radiological review at final follow-up (67.9%). Average patient age was 68 years (42–70 years), 60.4% were female and the average BMI was 27.4 kg/m^2 (24.1–29.2) (Table 2).

Sixteen studies measured subsidence using Radiostereometric Analysis (RSA),[8,16,19–22,29–32,34,35,37–40] 10 used measurements on plain X-rays[15,17,18,24–28,33,36] and two used Ein Bild Roentgen Analyse (EBRA, Table 3).[23,41] Twelve papers used the HHS[15,17,21,24,26,28,33,36,37,39–41] and six the OHS.[8,19,24,25,28,38]

Quality assessment

Amongst the included studies were six randomized controlled trials.[8,16,19,32,37,40] All papers included in this study were assessed to be of good or fair quality.

Details of surgical technique

A single surgical approach was used in 16 studies,[8,16,30,33,37–40,18–23,25,29] with multiple approaches in nine[15,17,24,26,27,31,32,35,41] and three failing to detail the approach used (Table 4).[28,34,36]
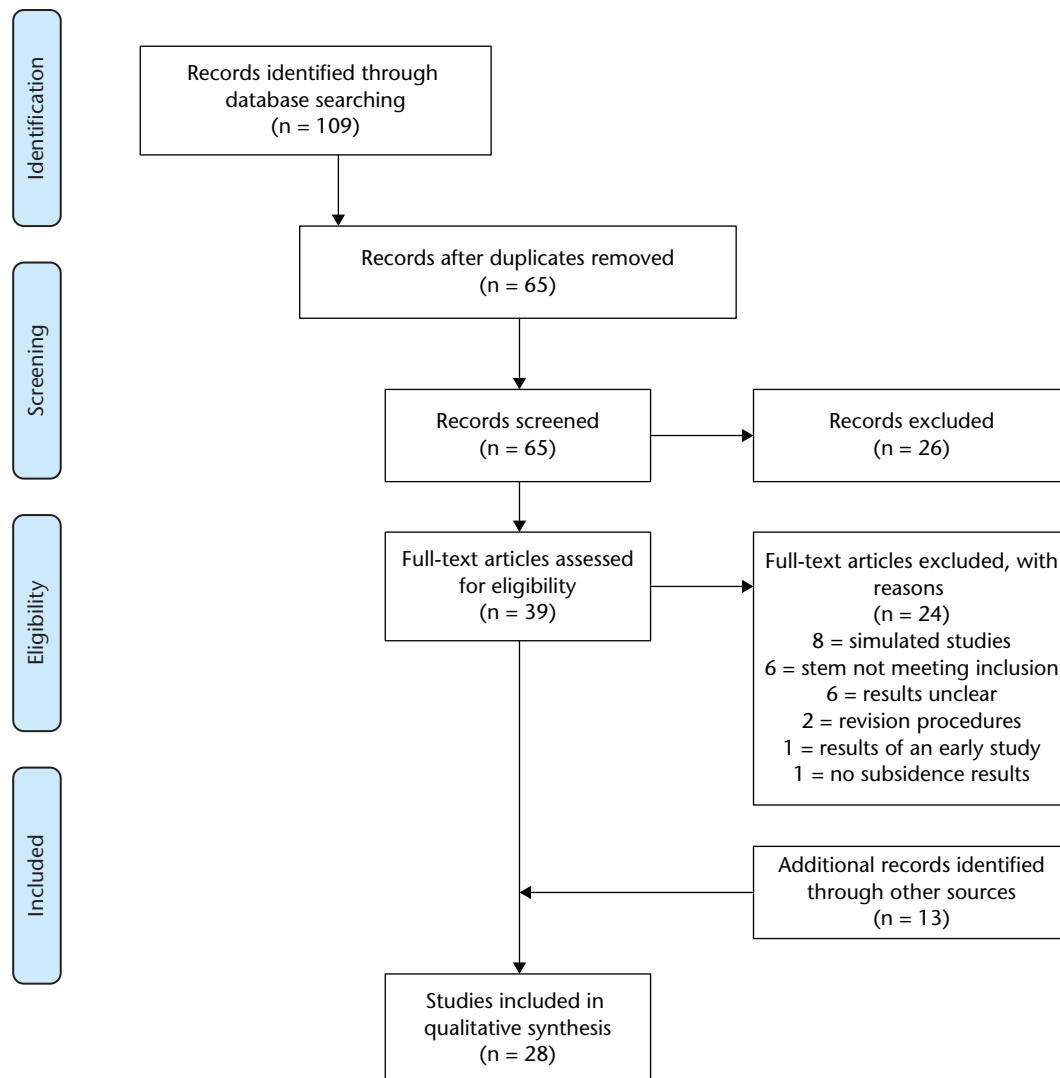
Fig. 1 PRISMA flowchart.

Third generation femoral cementing was used in 14 studies[16,19–21,24,26,29–33,36,40,41] and second generation in four.[15,17,18,25] Ten studies failed to specify the cementing technique used[8,22,23,27,28,34,35,37–39] and five of these also failed to specify the type of cement.[23,27,28,34,38] Nine studies documented the use of a centralizer[16,20,21,24,26,29,33,39,40] and 15 the use of a restrictor (Table 4).[15,17,18,21,25–27,29,31–33,35,36,38,41]

The type of acetabular component was specified in 20 of the papers,[8,15,17–20,23–28,31–33,35–37,39,41] with 10 using a consistent femoral and acetabular implant combination.[8,19,20,23,31,32,35–37,39] A single acetabular design was used in eight studies, five being cemented[8,23,31,35,39] and three uncemented.[19,32,36]

Clinical outcomes

Of the 12 papers that used the HHS,[15,17,21,24,26,28,33,36,37,39,40,41] 11 had both pre-operative and post-operative scores.

The average pre-operative score was 42.4, improving to 84.7 after surgery at an average follow-up of 7.1 years.[15,17,21,26,28,33,36,37,39,40,41]

The OHS was used in six papers,[8,19,24,25,28,38] but only two included both pre-operative and post-operative results, with an average pre-operative OHS of 20.4 improving to 42.0 at an average follow-up of 5.5 years.[8,28]

Radiological outcomes

There were 2099 hips available at the time of the final radiological review, 1759 double-tapers (83.8%) and 340 triple-tapers (16.2%) (Tables 5 and 6). Thirteen papers included the Barrack grading,[8,15,17–19,25–28,33,36,40,41] with the majority of the hips being Grade A or B (Table 7). Eight papers specifically commented on distal femoral cortical hypertrophy (DFCH).[15,17,18,22,24–26,33] Two papers reported the absence of DFCH.[15,26] The six papers reporting its presence featured the use of double-tapered stems, with the

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Table 2. Study demographics

Paper	Stem design	Average patient age	Gender (% female)	BMI (kg/m²)	Total number of hips enrolled	Hips radiologically analysed at final follow-up	% analysed at final follow-up
Alfaro-Adrian 1999[29]	Exeter	66.0	50.0%	–	14	14	100.0%
Glyn-Jones 2003[35]	Exeter[a]	70.0	–	–	18	18	100.0%
	Exeter[b]	68.0	–	–	16	16	100.0%
	Exeter[c]	68.0	–	–	12	12	100.0%
Stefánsdóttir 2004[22]	Exeter	63.0	40.9%	–	22	22	100.0%
Glyn-Jones 2005[30]	Exeter	70.0	–	–	21	21	100.0%
	CPS Plus	69.0	–	–	21	21	100.0%
Nelissen 2005[40]	Exeter	71.0	–	26.0	22	19	86.4%
	Exeter	71.0	–	26.0	19	11	57.9%
Glyn-Jones 2006[31]	Exeter[d]	68.0	–	–	19	19	100.0%
	Exeter[e]	70.0	–	–	26	26	100.0%
Hook 2006[25]	Exeter	61.0	64.9%	–	142	86	60.6%
Li 2007[34]	Exeter	70.5	36.4%	26.6	11	11	100.0%
Lewthwaite 2008[27]	Exeter	42.0	–	–	130	123	94.6%
Carrington 2009[24]	Exeter	67.6	59.1%	–	325	106	32.6%
Bohm 2012[32]	Exeter[f]	73.0	–	–	21	14	66.7%
	Exeter[g]	72.0	–	–	20	11	55.0%
Nieuwenhuijse 2012[39]	Exeter	70.0	84.6%	–	41	24	58.5%
Murray 2013[38]	Exeter	63.0	50.0%	–	20	20	100.0%
Park 2015[33]	Exeter	57.0	42.9%	–	91	91	100.0%
Westerman 2018[28]	Exeter	67.7	62.8%	–	540	374	69.3%
Clement 2019[23]	Exeter	69.9	57.5%	–	200	140	70.0%
Yates 2002[18]	CPT	65.0	68.0%	–	108	76	70.4%
Kaneuji 2006[36]	CPT	69.1	81.6%	24.1	42	42	100.0%
Yates 2008[17]	CPT	62.3	70.0%	–	191	120	62.8%
Burston 2012[15]	CPT	60.0	64.4%	–	191	90	47.1%
Jørgensen 2019[19]	CPT[h]	76.0	48.0%	29.0	25	24	96.0%
	CPT[i]	76.0	66.7%	29.0	27	24	88.9%
Ek 2005[26]	C-stem	70.2	51.0%	28.1	200	162	81.0%
	Exeter	68.4	59.8%	28.5	205	145	70.7%
Von Schewelov 2014[21]	C-stem	66.0	57.6%	–	36	14	38.9%
Flatøy 2015[8]	C-stem	66.0	65.4%	25.0	35	26	74.3%
	Exeter	65.0	76.0%	28.0	34	25	73.5%
Olerud 2014[20]	MS-30[j]	68.4	46.7%	29.0	30	28	93.3%
	MS-30[k]	68.4	71.4%	29.2	21	19	90.5%
Weber 2017[16]	MS-30[l]	69.0	43.3%	29.0	30	10	33.3%
	MS-30[m]	71.0	66.7%	27.0	30	16	53.3%
Madörin 2019[41]	TwinSys	79.0	52.6%	25.4	100	49	49.0%
McCalden 2010[37]	CPCS	75.7	81.3%	–	17	16	94.1%
	Exeter	77.9	85.7%	–	17	14	82.4%
	Total	68*	60.9%*	27.3*	3090	2099	67.9%

[a]With simplex cement. [b]With CMW3 cement. [c]With CMW1 cement. [d]Posterior approach. [e]Anterolateral approach. [f]Simplex T cement. [g]Simplex P cement. [h]Hifaitgue G cement. [i]Palacos R+G cement. [j]Palacos cement. [k]Refobicin cement. [l]Hollow centralizer. [m]Solid centralizer. *Average.

Table 3. Demographics by method of analysis

Radiological analysis method	Number of hips recruited	Number of hips available for radiological analysis	Average age	Gender (% female)	BMI	Average follow-up (years)
Plain radiograph	2165	1415 (65.4%)	62.8	61.0%	26.9	9.5
RSA	625	495 (79.2%)	69.7	61.4%	27.6	3.5
EBRA	300	189 (63.0%)	74.5	55.9%	25.4	3.5

Notes. RSA, Radiostereometric Analysis; EBRA, Ein Bild Roentgen Analyse; BMI, body mass index.

reported incidence ranging from 0.83% to 10.3% (Table 4).[17,18,22,24,25,33]

Subsidence at one year

Eight papers quoted one-year subsidence values (Table 8),[16,17,19,22,29,35,36,40] with four looking at different variables using the same prosthesis.[16,19,35,40] The overall mean subsidence at one year was 0.97 mm, for double-tapers it was 1.01 mm and for triple-tapers 0.75 mm. Six papers used RSA and two used radiographs. The mean subsidence for the RSA papers was 1.00 mm and for radiograph papers 0.76 mm (Table 9). There was no significant difference between the subsidence of double and triple-tapered implants at one year (p = 0.2432).

Table 4. Study surgical technique and outcomes of interest

Paper	Stem	Cement	Technique	Restrictor	Centralizer	Approach	Subsidence (mm)						Into valgus	DFCH
							1y	2y	5y	10y	12–13y	15–16y		
Alfaro-Adrian 1999[29]	Exeter	CMW	3rd generation	Y	Y	Anterolateral	1.06	1.20	–	–	–	–	–	–
Glyn-Jones 2003[35]	Exeter	Simplex	–	Y	–	Combination	1.07	–	–	–	–	–	Y	–
		CMW3	–	Y	–	Combination	1.00	–	–	–	–	–	Y	–
		CMW1	–	Y	–	Combination	1.26	–	–	–	–	–	Y	–
Stefánsdóttir 2004[22]	Exeter	Palcos with gent	–	–	–	Posterolateral	1.23	1.34	1.77	–	–	–	22.73%	2
Glyn-Jones 2005[30]	Exeter	CMW3	3rd generation	–	–	Hardinge	–	0.86	–	–	–	–	Y	–
	CPS Plus	CMW3	3rd generation	–	–	Hardinge	–	0.67	–	–	–	–	N	–
Nelissen 2005[40]	Exeter	Simplex P	3rd generation	–	Y	Lateral	1.05	1.53	–	–	–	–	0%	–
	Exeter	Simplex AF	3rd generation	–	Y	Lateral	0.95	1.12	–	–	–	–	0%	–
Glyn-Jones 2006[31]	Exeter	CMW3G	3rd generation	Y	–	Posterolateral	–	1.15	–	–	–	–	Y	–
	Exeter	CMW3G	3rd generation	Y	–	Hardinge	–	1.01	–	–	–	–	Y	–
Hook 2006[25]	Exeter	Palacos R with gent	2nd generation	Y	–	Posterolateral	–	0.50	–	–	1.52	–	2.27%	7
Li 2007[34]	Exeter	–	–	Y	Y	–	–	1.10	1.40	–	–	–	Y	–
Lewthwaite 2008[27]	Exeter	–	–	Y	–	Combination	–	–	–	–	1.29	–	–	–
Carrington 2009[24]	Exeter	Simplex RO	3rd generation	–	Y	Combination	–	–	–	1.32	–	1.82	–	11
Bohm 2012[32]	Exeter	Simplex T	3rd generation	Y	–	Combination	–	0.66	–	–	–	–	–	–
	Exeter	Simplex P	3rd generation	Y	–	Combination	–	0.71	–	–	–	–	–	–
Nieuwenhuijse 2012[39]	Exeter	Simplex AF / P	–	–	Y	Lateral	–	1.42	1.89	2.13	–	–	–	–
Murray 2013[38]	Exeter	–	–	Y	–	Anterolateral	–	0.92	–	1.28	–	–	–	–
Park 2015[33]	Exeter	Simplex	3rd generation	Y	–	Hardinge	–	–	–	–	1.90	–	–	3
Westerman 2018[28]	Exeter	–	–	–	–	–	–	–	–	–	1.20	–	–	–
Clement 2019[23]	Exeter	–	–	–	–	Posterolateral	–	1.20	–	–	–	–	Y	–
Yates 2002[18]	CPT	Palacos R	2nd generation	–	Y	Posterolateral	–	1.08	2.18	–	–	–	–	5
Kaneuji 2006[36]	CPT	Endurance CMW	3rd generation	Y	–	–	0.72	–	–	–	–	–	–	–
Yates 2008[17]	CPT	Palacos R	2nd generation	–	Y	Combination	0.80	–	–	–	–	–	5.0%	1
Burston 2012[15]	CPT	Palacos R with gent	2nd generation	Y	–	Combination	–	–	–	1.95	–	2.10	–	0
Jørgensen 2019[19]	CPT	Hi fatigue G	3rd generation	–	–	Posterolateral	0.91	1.12	–	–	–	–	–	–
		Palacos R+G	3rd generation	–	–	Posterolateral	1.03	1.19	–	–	–	–	–	–
Ek 2005[26]	C-stem	Endurance CMW	3rd generation	Y	Y	Anterolateral	–	0.77[a]	–	–	–	–	2.5%	0
	Exeter	Endurance CMW	3rd generation	Y	Y	Combination	–	0.82[b]	–	–	–	–	–	0
Flatøy 2015[8]	C-stem	Palacos R with gent	–	–	–	Hardinge	–	1.28	–	–	–	–	11.5%	–
	Exeter	Palacos R with gent	–	–	–	Hardinge	–	1.67	–	–	–	–	12.0%	–
Von Schewelov 2014[21]	C-stem	Palacos with gent	3rd generation	Y	Y	Hardinge	–	1.35	1.71	2.06	–	–	–	–
Olerud 2014[20]	MS-30	Palacos	3rd generation	–	Y	Posterolateral	–	1.40	–	–	–	–	–	–
		Refobicin	3rd generation	–	Y	Posterolateral	–	1.28	–	–	–	–	–	–
Weber 2017[16]	MS-30	Palacos with gent	3rd generation	–	Y- Hollow	Posterolateral	1.21	1.40	1.74	1.99	–	–	–	–
	MS-30	Palacos with gent	3rd generation	–	Y- Solid	Posterolateral	0.28	0.28	0.36	0.57	–	–	–	–
Madörin 2019[41]	twinSys	Palacos R+G	3rd generation	Y	–	Combination	–	0.40	0.70	–	–	–	14.0%	–
McCalden 2010[37]	CPCS	Simplex	–	–	–	Hardinge	–	0.77	–	–	–	–	Y	–
	Exeter	Simplex	–	–	–	Hardinge	–	1.25	–	–	–	–	–	–

Notes. DFCH, distal femoral cortical hypertrophy.

[a]Mean at 2.4 years. [b]Mean at 2.6 years.

Subsidence at two years

Nineteen studies reported subsidence at two years[8,16,18–23,25,29–32,34,37–41] and three of these reported two-year data consistent with the trends demonstrated at one year (Table 8).[16,19,40] The overall mean subsidence at two years was 1.07 mm, for double-tapers it was 1.04 mm and for triple-tapers 1.02 mm. Fifteen papers used RSA, two used EBRA and two used radiographs. Mean subsidence for the RSA papers was 1.11 mm, for EBRA it was 0.80 mm and for radiograph papers it was 0.79 mm (Table 9). There was no significant difference between the subsidence of double and triple-tapered implants at two years (p = 0.4535).

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Table 5. Demographics by stem geometry

Stem geometry	Number of hips recruited	Number of hips available for radiological analysis	Average age	Gender (% female)	BMI	Average follow-up (years)
Double taper	2591	1759 (67.9%)	67.3	61.8%	27.2	5.1
Triple taper	499	340 (68.1%)	70.4	54.7%	27.5	5.0

Notes. BMI, body mass index.

Table 6. Summary of prosthesis used and numbers at final radiological follow-up

	Prosthesis	Papers used	Number of hips available for radiological review
Double taper (1759 hips)*	Exeter	Ek[26], Flatøy[8], Glyn-Jones 2003[35], 2005[30] & 2006[31], McCalden[37], Murray[38], Nieuwenhuijse[39], Nelissen[40], Stefánsdóttir[22], Clement[23], Carrington[24], Hook[25], Lewthwaite[27], Westerman[28], Alfaro-Adrian[29], Bohm[32], Park[33], Li[34]	1362 (77.4%)
	CPT	Burston[15], Kaneuji[36], Yates 2002[18] & 2008[17], Jørgensen[19]	376 (21.4%)
	CPS plus	Glyn-Jones 2005[30]	21 (1.2%)
Triple taper (340 hips)*	C-stem	Ek[26], Flatøy[8], von Schewelov[21]	202 (59.4%)
	MS-30	Weber[16], Olerud[20]	73 (21.5%)
	TwinSys	Madörin[41]	49 (14.4%)
	CPCS	McCalden[37]	16 (4.7%)

*Hips available for radiological review at final follow-up.

Table 7. Summary of papers quoting the Barrack grading of cement mantles

Paper	Prosthesis	Barrack A	Barrack B	Barrack C	Barrack D
Nelissen 2005[40]	Exeter	30.00%	70.00%	–	–
		68.42%	31.58%	–	–
Hook 2006[25]	Exeter	72.00%	0.00%	24.00%	4.00%
Lewthwaite 2008[27]	Exeter	33.33%	42.50%	22.50%	1.67%
Park 2015[33]	Exeter	54.95%	35.16%	9.89%	0.00%
Westerman 2018[28]	Exeter	73.60%	25.00%	1.40%	0.00%
Yates 2002[18]	CPT	67.10%	2.60%	30.30%	0.00%
Kaneuji 2006[36]	CPT	30.95%	42.86%	26.19%	0.00%
Yates 2008[17]	CPT	76.00%	0.00%	20.00%	3.30%
Burston 2012[15]	CPT	72.00%	0.00%	23.00%	5.00%
Jørgensen 2019[19]	CPT[a]	96.00%	4.00%	0.00%	0.00%
	CPT[b]	57.69%	38.46%	3.85%	0.00%
EK 2005[26]	C-Stem	45.70%	46.30%	8.00%	0.00%
	Exeter	36.50%	56.60%	6.90%	0.00%
Flatøy 2015[8]	C-Stem	34.62%	50.00%	15.38%	0.00%
	Exeter	36.00%	52.00%	12.00%	0.00%
Madörin 2019[41]	twinSys	47.00%	44.00%	7.00%	1.00%

[a]Hi Fatigue. [b]Palacos R&G.

Subsidence at five years

Seven papers reported subsidence at five years (Table 8),[16,18,21,22,34,39,41] with three studies again reporting results consistent with their one and/or two-year findings.[16,21,39] The overall mean subsidence at five years was 1.47 mm, for double-tapers it was 1.81 mm and for triple-tapers 1.13 mm. Five papers used RSA, one used EBRA and one used radiographs. Mean subsidence for the RSA papers was 1.48 mm, for EBRA was 0.70 mm and for the single radiograph paper 2.18 mm (Table 9). There was no significant difference between

the subsidence of double and triple-tapered implants at five years (p = 0.0787).

Subsidence at 10 years

Six papers reported a 10-year subsidence value (Table 8),[15,16,21,24,38,39] with three papers again reporting results consistent with their earlier findings.[16,21,39] The overall mean 10-year subsidence was 1.61 mm, for double-tapers it was 1.67 mm and for triple-tapers 1.54 mm. Four papers used RSA and two used radiographs. Mean subsidence for the RSA papers was 1.61 mm and for the

Table 8. Summary of subsidence values at time intervals

Year	Paper	Prosthesis	Radiographic Analysis	Subsidence	Mean subsidence at time
1 Year	Alfaro-Adrian 1999[29]	Exeter	RSA	1.06 mm	0.97 mm
	Glyn-Jones 2003[35]	Exeter	RSA	1.07 mm	
				1.00 mm	
				1.26 mm	
	Stefánsdóttir 2004[22]	Exeter	RSA	1.23 mm	
	Nelissen 2005[40]	Exeter	RSA	1.05 mm	
				0.95 mm	
	Kaneuji 2006[36]	CPT	X-ray	0.72 mm	
	Yates 2008[17]	CPT	X-ray	0.80 mm	
	Jørgensen 2019[19]	CPT	RSA	0.91 mm	
				1.03 mm	
	Weber 2017[16]	MS-30*	RSA	1.21 mm	
				0.28 mm	
2 Years	Alfaro-Adrian 1999[29]	Exeter	RSA	1.20 mm	1.07 mm
	Stefánsdóttir 2004[22]	Exeter	RSA	1.34 mm	
	Glyn-Jones 2005[30]	Exeter	RSA	0.86 mm	
		CPS Plus		0.67 mm	
	Nelissen 2005[40]	Exeter	RSA	1.53 mm	
				1.12 mm	
	Glyn Jones 2006[31]	Exeter	RSA	1.15 mm	
				1.01 mm	
	Hook 2006[25]	Exeter	X-ray	0.50 mm	
	Li 2007[34]	Exeter	RSA	1.10 mm	
	Bohm 2012[32]	Exeter	RSA	0.66 mm	
				0.71 mm	
	Nieuwenhuijse 2012[39]	Exeter	RSA	1.42 mm	
	Murray 2013[38]	Exeter	RSA	0.92 mm	
	Clement 2019[23]	Exeter	EBRA	1.20 mm	
	Yates 2002[18]	CPT	X-ray	1.08 mm	
	Jørgensen 2019[19]	CPT	RSA	1.12 mm	
				1.19 mm	
	Von Schewelov 2014[21]	C-Stem*	RSA	1.35 mm	
	Flatøy 2015[8]	C-Stem*	RSA	1.28 mm	
		Exeter		1.67 mm	
	Olerud 2014[20]	MS-30*	RSA	1.40 mm	
				1.28 mm	
	Weber 2017[16]	MS-30*	RSA	1.40 mm	
				0.28 mm	
	Madörin 2019[41]	TwinSys*	EBRA	0.40 mm	
	McCalden 2010[37]	CPCS*	RSA	0.77 mm	
		Exeter		1.25 mm	
5 years	Stefánsdóttir 2004[22]	Exeter	RSA	1.77 mm	1.47 mm
	Li 2007[34]	Exeter	RSA	1.40 mm	
	Nieuwenhuijse 2012[39]	Exeter	RSA	1.89 mm	
	Yates 2002[18]	CPT	X-ray	2.18 mm	
	Von Schewelov 2014[21]	C-Stem*	RSA	1.71 mm	
	Weber 2017[16]	MS-30*	RSA	1.74 mm	
				0.36 mm	
	Madörin 2019[41]	TwinSys*	EBRA	0.70 mm	
10 years	Carrington 2009[24]	Exeter	X-ray	1.32 mm	1.61 mm
	Nieuwenhuijse 2012[39]	Exeter	RSA	2.13 mm	
	Murray 2013[38]	Exeter	RSA	1.28 mm	
	Burston 2012[15]	CPT	X-ray	1.95 mm	
	Von Schewelov 2014[21]	C-stem*	RSA	2.06 mm	
	Weber 2017[16]	MS-30*	RSA	1.99 mm	
				0.57 mm	
12–13 years	Hook 2006[25]	Exeter	X-ray	1.52 mm	1.48 mm
	Lewthwaite 2008[27]	Exeter	X-ray	1.29 mm	
	Westerman 2018[28]	Exeter	X-ray	1.20 mm	
	Park 2015[33]	Exeter	X-ray	1.90 mm	
15–16 years	Carrington 2009[24]	Exeter	X-ray	1.82 mm	1.96 mm
	Burston 2012[15]	CPT	X-ray	2.10 mm	

Notes. RSA, Radiostereometric Analysis; EBRA, Ein Bild Roentgen Analyse.

*Denotes triple-tapered stem.

Table 9. Summary of subsidence values

Time (years)	Subsidence (mm)	Stem design		Method of subsidence measurement		
	Overall	Double taper	Triple taper	RSA	Radiograph	EBRA
1	0.97	1.01	0.75	1.00	0.76	–
2	1.07	1.04	1.02	1.11	0.79	0.80
5	1.47	1.81	1.13	1.48	2.18*	0.70*
10	1.61	1.67	1.54	1.61	1.64	–
12–13	1.48	1.48	–	–	1.48	–
15–16	1.96	1.96	–	–	1.96	–

*Based on one paper.

Table 10. Calculated subsidence rates

Paper	Stem	Subsidence rate per year (mm)			
		1–5 years	2–5 years	1–10 years	2–10 years
Stefánsdóttir 2004[22]	Exeter	0.14	0.11	–	–
Li 2007[34]	Exeter	–	0.10	–	–
Nieuwenhuijse 2012[39]	Exeter	–	0.16	–	0.09
Murray 2013[38]	Exeter	–	–	–	0.05
Yates 2002[18]	CPT	–	0.37	–	–
Madörin 2019[41]	twinSys*	–	0.10	–	–
Von Schewelov 2014[21]	C-stem*	–	0.12	–	0.09
Weber 2017[16]	MS-30[1]*	0.13	0.11	0.09	0.07
	MS-30[2]*	0.02	0.03	0.03	0.04

[a]Hollow centralizer. [b]Solid centralizer. *Triple-tapered stem.

radiograph papers was 1.64 mm (Table 9). There was no difference between the subsidence of double and triple-tapered implants at 10 years (p = 0.4535).

Subsidence at other time points

Four papers reported subsidence between 11 and 14 years with a mean follow-up of 12.6 years. All four used double-tapered stems and radiographs to assess subsidence, with a mean subsidence of 1.48 mm (Tables 8 and 9).[25,27,28,33] Two papers reported mean subsidence between 15 and 16 years with a mean follow-up of 15.8 years. Both used double-tapered stems and radiographs to assess subsidence, with a mean subsidence of 1.96 mm (Tables 8 and 9).[15,24]

Migration into valgus

Thirteen papers commented on the presence or absence of migration into valgus (Table 4),[8,17,22,23,25,26,30,31,34,35,37,40,41] with six reporting that the stem migrated into a more valgus alignment.[8,17,22,25,26,41]

Mean overall subsidence

To explore the effect of the method of radiological evaluation on mean overall subsidence, a weighted Analysis of Variance (ANOVA) was performed, which found no significant difference between the methods (p = 0.4295). The pairwise contrasts between each type of measurement demonstrated no statistically significant difference between any pair of measurement types (EBRA vs. radiographic, p = 0.2245; EBRA vs. RSA, p = 0.4785; and radiographic vs. RSA, p = 0.5314).

The mean overall subsidence in double and triple-tapered stems was 1.33 mm and 0.91 mm respectively, and this difference was significant and remained so even after controlling for radiological measurement type (p = 0.0342).

Subsidence rates

In addition to the mean subsidence values, a calculation was performed on all papers offering one or two-year subsidence rates with subsequent five or 10-year values, in order to work out subsidence rates over time (Table 10).

Rates were calculated by subtracting the one or two-year value from the five or 10-year value and dividing by the difference in years. For example: (five-year value – one year value) ÷ (five – one).

There was no significant difference in subsidence between double-tapered and triple-tapered stems between two and five years (p = 0.2017) or between two and 10 years (p = 0.8982) (Table 10).

Discussion

Despite the already widespread use and increasing popularity of cemented, polished femoral implants adhering to the taper-slip philosophy, the magnitude and duration of subsidence compatible with excellent clinical performance and survivorship has yet to be fully established. Previous studies have attempted to establish a threshold for migration at two years, above which a high probability of failure could be predicted.[42–45] A wide range of levels has been suggested, from 0.15 to 1.2 mm,[42,43,45] but these were all based on the performance of composite beam stems, which were not designed to subside and could not therefore be applied to taper-slip implants.[44,46–48]

Teeter et al,[44] using the thresholds proposed by Kärrholm et al and van der Voort et al,[42,45] examined subsidence with three stem designs, one composite beam and two taper-slip. They found that whilst the taper-slip stems exceeded the proposed subsidence threshold at two years, the composite beam did not. Despite this, the 10-year revision rates for the taper-slip Exeter (Stryker-Howmedica, Middlesex, UK) and CPCS (Smith & Nephew, Memphis, USA) stems were 3.9% and 4.3% respectively compared to 5.6% with the composite beam Spectron EF (Smith & Nephew, Memphis, USA).[44]

The current review reports the subsidence of taper-slip stems up to a mean of 15.8 years and found that at all time points, the double-tapered stems subsided more than the triple-tapers, but that this did not reach statistical significance (p = 0.2432, 0.4535, 0.0787 and 0.7256 at one, two, five and 10 years respectively). The difference

in mean overall subsidence between double and triple-tapered stems was statistically significant (1.33 mm vs. 0.91 mm; p = 0.0342), however, there is no evidence that this resulted in clinical significance.

The addition of a third taper, running from the lateral shoulder to the medial aspect of the implant, is designed to produce more physiological loading of the proximal femur leading to better stress distribution through the cement mantle[49] and a reduction in negative bone remodelling with time.

The current review found that double-tapered stems have a higher rate of migration in the first year compared with triple-tapers, but between years one and two, triple-tapered stems subside at a greater rate. There was no significant difference in subsidence at any time point between the two stem geometries. However, mean overall subsidence was significantly affected by stem geometry (double versus triple tapers).

When directly comparing double and triple-tapered stems, Flatøy et al found significantly lower subsidence at three months for triple-tapers, but during the second year, the rate was similar.[8] McCalden et al found a significantly reduced level of subsidence in triple-tapers at two years and proposed that the broader proximal cross-section of the CPCS stem was a factor in reducing subsidence compared to the Exeter,[37] whereas Ek et al and Jayasuriya et al found similar levels of subsidence at all time points.[26,50]

The method of measuring subsidence varied between studies, with the majority being RSA based. RSA has been used to study early stem migration and correctly predicted the poor long-term performance of the composite beam Charnley Elite-Plus stem (De Puy International, Leeds, UK).[51] Other studies have, however, demonstrated that such predictions are not always accurate.[21,52]

In 1999, Nivbrant et al reported early RSA results for the composite beam Scientific Hip Prosthesis (Biomet, Indiana, USA), finding increased subsidence and retroversion, suggesting the likelihood of failure.[53] However, when Van de Groes et al reported the longer-term results in 2012, they found a satisfactory survival rate of 98.8% at 10 years.[52] In 2005, Sundberg et al reported two-year RSA results for the triple-tapered C-stem, finding increased posterior migration and retroversion, which were predicted to result in a high failure rate.[54] These fears were subsequently dispelled by von Schewelov et al in 2014 who reported excellent 10-year results for the same cohort,[21] indicating that caution should be used when interpreting early RSA results, especially when the long-term pattern of migration of a particular implant is not known.

In this systematic review, cohorts analysed using RSA were usually of less than 30 patients with high levels of exclusion due to technical issues including poor image quality or loss of markers (Table 2). Despite these limitations, RSA is seen as the current gold standard for assessment of migration due to its accuracy in detecting outlier implants.[42] EBRA was used in only two papers and had a similarly high exclusion rate due to the requirement for a minimum number of standardized radiographs. However, the use of EBRA has been shown to improve the accuracy of migration assessment, particularly vertically, compared to plain radiographic measurements (Table 2).[55] The measurement of plain radiographs using the Fowler technique[56] was the second most frequently used method, with these papers having larger patient numbers and longer follow-up. The benefit of the Fowler technique is that special markers and or software are not required to perform the migration assessment. However, this means that the accuracy of measurements are operator dependent and can vary depending on the position and magnification of the radiograph.

At one year, Glyn-Jones et al found that different cement viscosities had no effect on subsidence with Exeter stems[35] and Nelissen et al found no association between cement viscosity, mantle thickness and migration.[40] Jørgensen et al found no significant difference in subsidence between two types of cement,[19] but Weber et al found a significantly increased subsidence when using a hollow rather than a solid centralizer.[16]

At two years there was no statistically significant difference between the distal migration of Exeter and CPS Plus double-tapered stems, although subsidence, internal rotation and valgus angulation were lower in the CPS Plus stem, which had a wider, more rectangular proximal section.[30] Two papers demonstrated lower subsidence in triple-tapered stems compared to doubles[8,37] (Tables 6 and 7) and two more concluded that there were no significant differences in subsidence rates due to the use of different antibiotics in the cement.[20,32] Glyn-Jones et al found no statistically significant difference in distal subsidence between posterior and anterolateral approaches, although the posterior approach group had significantly higher posterior head migration (1.27 vs. 0.77 mm) and internal rotation (1.94 vs. 1.16 degrees).[31]

The mean subsidence at two years based on plain radiographic measurements and EBRA was similar (0.79 mm vs. 0.80 mm) and the mean subsidence at 10 years, reported in papers based on both RSA and plain radiographic measurements was again similar (1.62 mm vs. 1.64 mm). Our analysis found no significant difference between the method of measurement used and the effect on reported subsidence (Table 9).

Two of the three studies comparing a double-tapered stem with a triple-taper reported that the triple-taper migrated into valgus whilst the double-taper tended to migrate into varus,[29,34] whereas Flatøy et al reported both designs migrating into valgus.[8] Glyn-Jones et al compared the use of three different types of cement describing valgus migration with a double-tapered stem in all three

cohorts[35] and in a comparison of the posterior with the anterolateral approach, both demonstrated migration into valgus, but there was no significant difference in the amount produced.[31] In a study of two different double-tapered stems, the CPS Plus (Endoplus, Swindon, UK) with a wider, more rectangular proximal section, did not migrate into valgus or internal rotation compared with the Exeter stem which did (Stryker-Howmedica, Middlesex, UK),[30] suggesting that the specifics of the geometry of a design were integral to the rate of subsidence and not just the number of planes that tapered.

Barrack grading of the cement mantle has been demonstrated to be an independent predictor of stem failure.[13] Several studies reported a significant increase in subsidence with increasing Barrack grade,[18,41,57,58] whilst others did not.[15,17,28] Yates et al found that implants with a Grade A mantle had subsided less than those with a Grade D at 10 years (1.67 mm vs. 2.5 mm), but that this was not statistically significant[17] and Hook et al reported higher subsidence with an increased Barrack grade but did not comment on the significance.[25] There was therefore no clear agreement as to whether Barrack grade is related to subsidence, but, in any case, increased subsidence is not necessarily detrimental to the overall performance of taper-slip stems.

The presence or absence of DFCH was reported in eight papers (Table 7), six of which had patients with DFCH. Two studies reported that the presence of DFCH was not related to subsidence, although Yates et al found that DFCH occurred twice as frequently in hips with cement mantle defects.[18,25] Park et al found that patients with DFCH had less subsidence than the overall mean (< 1 mm vs. 1.90 mm)[33] and Carrington et al found a similar trend (1.59 mm vs. 1.82 mm).[24] Both papers concluded that DFCH was related to the use of larger stems, which subsided less. Only one paper specifically mentioned clinical outcome with regard to DFCH, stating there was no correlation between DFCH and poor clinical outcome.[22] This is in keeping with the literature, where the outcome of patients displaying DFCH was no worse than those not displaying DFCH.[59–61]

This systematic review is strengthened by the large number of papers included; the largest cohort in the literature for taper-slip stems. The papers covered a range of implants, including the Exeter stem, the most frequently used double-taper, and the C-stem, the most frequently used triple-taper. The papers included also covered a wide age range of patients, from a mean of 42 to a mean of 77.9 and values for subsidence consistent with good clinical results at a wide range of different time points ranging from one to more than 15 years. Amongst the included studies were six randomized controlled trials[8,16,19,32,37,40] further strengthening the evidence presented in this review.

The large dropout rates between initial recruitment and final radiological analysis (31.4%) were to be expected. In the papers with long-term follow-up this was inevitable, due to the expected patient death rates, and in the shorter-term RSA and EBRA studies this was the result of technical issues due to insufficient or technically inadequate radiographs. Whilst the dropout rates varied between papers, each study outcome was weighted according to the number of patients in that study such that greater patient numbers led to a higher weight being assigned to the study.

There was a lack of clarity in many papers regarding the type of cement used and the cementing technique making establishing the significance of these difficult. Of note, however, is the fact that in the papers comparing different cement types, no significant difference in subsidence was found.[19,20,32,35,40] There was also heterogeneity in the surgical approaches used, which potentially affects the interpretation of results due to the lack of standardization, although Glyn-Jones et al using a single implant and cement combination, concluded that the surgical approach used was not related to the magnitude of distal migration.[31]

There is, however, a potential bias towards the double-tapered stems in reporting, as they outnumbered the triple-tapered stems in hips recruited (2591 vs. 499) and in those analysed at final radiological follow-up (1759 vs. 340), although the studies directly comparing the two designs of stem found similar outcomes irrespective of subsidence.[8,26,37]

Conclusion

This systematic review evaluated the subsidence levels reported for clinically successful taper-slip stems at one, two, five and 10 years and found that the method used to measure subsidence did not have a significant influence. Whilst a subsidence threshold beyond which failure is more likely to occur could not be established based solely on the literature, the review reports the levels of subsidence at which clinical outcomes and survivorship remain excellent. More studies are, however, required into the longer-term performance of the triple-tapered stems, but as no significant differences were found in the subsidence between the two designs, the values set forth here can be applied to all taper-slip stems.

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