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Systematic Review

Does Direct Surgical Repair Benefit Pars Interarticularis Fracture? A Systematic Review and Meta-analysis

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Background: Promising results have been shown in previous studies from direct pars interarticularis repair. These include Scott wiring, Buck repair, pedicle screw repair, and Morscher techniques. In addition, several minimally invasive techniques have been reported to show high union rates, low rates of implant failure and wound complications, shorter length of stay, a lower postoperative pain score with faster recovery, and minimal blood loss

Objectives: To compare the evidence on techniques for direct pars interarticularis repair.

Study Design: Systematic review and meta-analysis.

Setting: Review article.

Methods: We conducted a comprehensive search of databases to identify studies assessing outcomes of direct pars interarticularis defect repair. Two authors independently screened electronic search results, performed study selection, and extracted data for meta-analysis. Sensitivity and subgroup analyses were performed to assess risk of bias.

Results: Forty studies were included in the final analysis. Union rate was higher in the pedicle screw repair group (effect size [ES] 95%; 95% CI, 86% to 100%), followed by the Buck repair group (ES 93%; 95% CI, 86% to 98%), Scott wiring (ES 85%; 95% CI, 63% to 99%), and Morscher method group (ES 63%; 95% CI, 2% to 100%). Positive functional outcome was higher for the Morscher method (ES 91%; 95% CI, 86% to 96%), followed by the Buck repair group (ES 85%; 95% CI, 68% to 97%), pedicle screw repair (ES 84%; 95% CI, 59% to 99%) and Scott repair group (ES 80%; 95% CI, 60% to 95%). Complication rates were highest among the Scott repair group (ES 12%; 95% CI, 4% to 22%) and Morscher method group (ES 12%; 95% CI, 0% to 34%).

Limitations: Heterogeneity of the included studies were noted. However, we performed sensitivity analyses from the available data to address this issue.

Conclusion: Our results indicate that pedicle screw repair and Buck repair may be associated with a higher union rate and lower complication rates compared to the Scott repair and Morscher method. Ultimately, the choice of technique should be based on the surgeon's preference and experience.

Key words: Pars interarticularis, pars fracture, direct repair, Buck repair, pedicle screw repair, Morscher method, Scott repair, minimally invasive pars repair, review

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Spondylolysis, defined as a defect in the pars interarticularis, is a common degenerative spine pathology with an incidence as high as 7% in the adult population, as reported in the literature (1). The vast majority of cases occur in the lower lumbar vertebra (L5); most patients are asymptomatic and unilateral (2). Although the cause of spondylolysis remains unknown, hereditary and acquired factors are both considered to contribute to the defect (3,4). The mechanism includes hyperextension and rotation of the spine. Risk factors include men, strenuous activities at a young age, repetitive axial loading, and hyperextension (5,6).

Conservative treatments, such as decreasing strenuous activities and bracing, are effective with early diagnosis and treatment (7,8). However, patients may require surgery if pain persists after 6 months of nonsurgical treatment (9).

Promising results have been shown in previous studies from direct pars interarticularis repair (10). These include Scott wiring, Buck repair, pedicle screw repair, and the Morscher technique. In addition, several minimally invasive techniques have been reported to show high union rates, low rates of implant failure and wound complications, a shorter length of hospital stay, and a lower postoperative pain score with faster recovery and minimal blood loss (11-20). In the current study, we performed a systematic review and meta-analysis to summarize the evidence on direct pars interarticularis repair techniques.

Methods

Search Strategy and Selection Criteria

A comprehensive search of the databases PubMed, Embase, Cochrane Central, Web of Science and Scopus, covering the period from 1946 through September 1st, 2020, was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (21). The search was limited to English language, human studies only. The search strategy was designed using the PICO approach (Population, Intervention, Comparator, and Outcomes) to address the following question: for patients with pars interarticularis defect undergoing surgery (Population), which direct pars interarticularis repair technique (Intervention/Comparator) is associated with superior outcomes (Outcomes)? The search was conducted by an experienced librarian with input from the study's principal investigator. Controlled vocabulary supplemented with keywords was used to search for studies describing the surgery for pars interarticularis defect repair. A description of the full search strategy is available in the supplementary material.

Data Extraction

Our meta-analysis included randomized controlled clinical trials, observational studies, case series, and case reports that compared patients who received different surgical interventions for a pars interarticularis defect (Fig. 1). Our inclusion criteria for the study populations were any patients who had

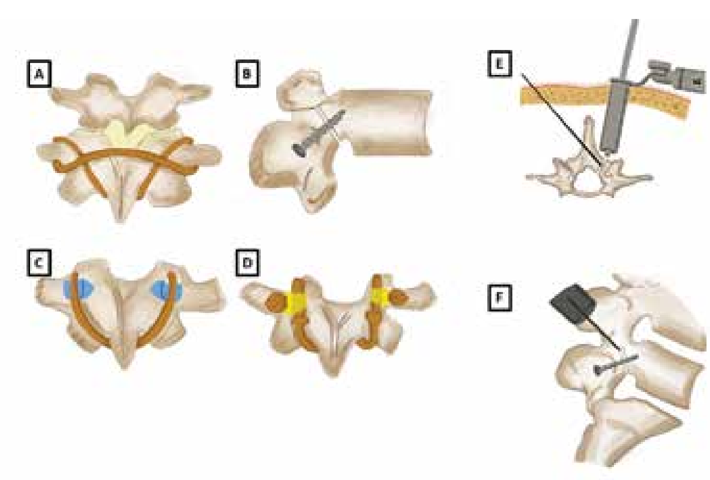

Fig. 1. *A summary of direct pars interarticularis repair techniques: A: Scott repair. The wire passes through the transverse processes and stabilizes the defect by wrapping around the spinous processes. B: Buck's repair. The screws are passed from the inferior edge of the lamina across the defect after placing the bone grafts into the defect C: Morscher repair. Bone grafts are placed into the defect. Then the screws are inserted in the superior articular processes followed by a hook hanging under the lamina. D: Pedicle screw with hooks/wire/rod. After pedicle screws are placed, lamina hooks/wire/rod are placed under the lamina. E.F. Endoscopic pars interarticularis repair. The spinal needle is inserted to navigate toward the pars defect under fluoroscopy. After bone grafts placed into the gap, a direct repair of the defect is performed with screws.*

received direct pars interarticularis repair surgery or minimally invasive techniques for spondylolysis, defined as small incisions less than 2 cm (Fig. 1). Patients were excluded if they had cancer, immunodeficiency, autoimmune conditions, or use of systemic corticosteroids. Studies that did not conform to our PICO or a wrong setting were also excluded. A wrong comparator could be excluded if comparing the following: with or without the use of bone grafts, 3D printing or robot assistance/guided, and fracture morphology. A wrong outcome could also be applied in articles that only described the surgical technique without reporting outcomes.

Two reviewers (SHLT, WCC) independently extracted information using a piloted data collection form, including general study characteristics and outcomes. General study characteristics included study origin (country), study design, study population inclusion and exclusion criteria, description of the experimental intervention, and potential effect modifiers like age, gender, race, and sports activities. Outcomes included the number of events and total number of patients in the intervention and control arms for binary outcomes, means, standard deviations, and group sizes for continuous outcomes and the adjusted effect estimates with 95% confidence intervals. We filtered studies that reported actual numbers versus percentages for the meta-analysis. All selected literature was documented in Covidence (www.covidence.org).

The reported primary outcome measures included union rates, implant failure rates, wound complication rates, and other complications. Data on other reported outcomes, including length of stay, surgical time, blood loss, patient reported outcomes, and pain intensity scores (Visual Analog Scale [VAS]) were also collected. Positive functional outcomes were defined as a postoperative Oswestry Disability Index (ODI) score less than 20, or excellent and good outcomes following the Henderson, Odom, and Macnab criteria. Two assessors (SHLT, WCC) independently reviewed all titles and abstracts. Articles were selected for full text review if inclusion criteria were met, based on agreement of the reviewers, with a low threshold for retrieval. Disagreements were resolved by discussion between the 2 reviewers; a third person was available when consensus could not be reached.

Quality Assessment

Two reviewers (SHLT, WCC) assessed the risk of bias using the Newcastle-Ottawa Scale for observational studies (22). Quality assessment was performed according to the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) scale (23) (Supplemental Tables 1 and 2).

Data Synthesis and Analysis

Union rate, implant failure rate, wound complications and other complications were summarized using pooled proportion of events (effect size [ES]), with corresponding 95% confidence intervals (CIs) calculated by the Wilson method (24). Continuous outcomes were pooled using weighted averages (WA) with standard deviations (SDs). Results are graphically represented by Forest plots (25). The Freeman-Tukey transformation was used to stabilize variance to include studies with a zero event rate (26). A random-effects model using the DerSimonian and Laird approach (27) was used to account for high heterogeneity (> 50%) between studies. Heterogeneity, or inconsistency of effect estimate, within studies, is quantified by Higgins I^2 (28). Heterogeneity and variability between subgroups indicate whether the pooled estimate from one of the devices is different from the others, represented by a *P* value. Between-study heterogeneity was assessed using Cochrane Q and I^2 statistics. According to the Cochrane handbook, heterogeneity is considered nonimportant with $I^2 < 30\%$, $P < 0.1$; moderate with $I^2 = 30\%$-60%; and substantial with $I^2 > 60\%$, $P > 0.1$. τ^2 is the variance of true effects, reflecting the amount of true heterogeneity. Hence, I2 may be viewed as the proportion of variability in the point estimates that is due to τ^2 rather than within-study error (29). Publication bias was evaluated by generating funnel plots and examining them for any obvious visual asymmetry (30). Sensitivity analyses were done to exclude studies reporting 100% fusion rates, 100% positive functional outcomes, no complications, and studies with less than one year follow-up. Subgroup analyses were done for studies with predominantly women and sporting populations. A *P* value < 0.05 was considered statistically significant. Statistical analysis was conducted using the Stata Statistical Software, Release 14 (StataCorp LLP).

Protocol and Registration

This systematic review was performed following the PRISMA statement. Additionally, it was recorded on the PROSPERO database (CRD42020199928).

Results

Study Results, Identification, Quality Assessment

The search identified 8,097 bibliographic references through the PubMed, Embase, Cochrane Central, Web of Science and Scopus databases (Fig. 2). After duplicate papers were removed, there were a total of 7,500 records in title and abstract form available for further screening. We excluded 7,417 clearly irrelevant references through a reading of the abstracts. Subsequently, we assessed 83 references for eligibility for our systematic review and meta-analysis. After scrutiny, we further excluded 38 of these references as they did not fulfil the inclusion criteria (11 studies had the wrong comparator, 5 the wrong language, 19 the wrong outcomes, one had the wrong study design, one the wrong intervention, and one study had the wrong population). Subsequently, 45 references met our inclusion criteria for this systematic review and meta-analysis. These studies were published from 2003 through 2019 (Table 1) (11-17,19,20,32-37,39-44,46-56,58-64,73).

We included studies after 2003 in order to make sur-

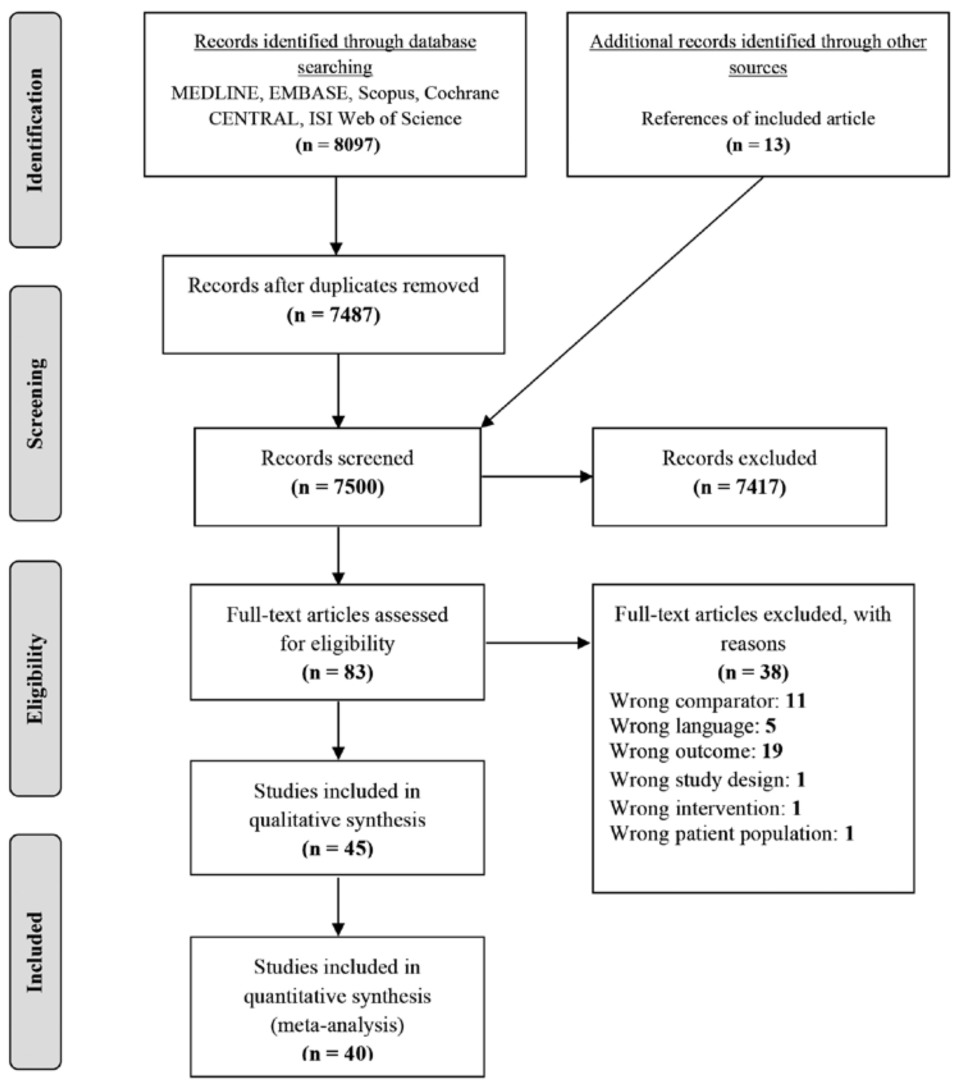

Fig. 2. *PRISMA flow diagram of the study.*

Table 1. *Baseline characteristics of included studies.*

References	Country	Study Design	Type of Surgery	Overall cohort							
				Patient Number	Gender: Women% (Men/ Women)	Mean Age (Range)	Follow-up (Months)	Associated Spondylolisthesis (n, %)	Mean Operation Time (Minutes)	Patient Population	Detail
Sairyo (31)	Japan	Case series	Endoscopic Buck Repair	7	42.86 (4/3)	60.9 (42-70)	11.7 (6-22)	3, 42.86	138(90-240)	Not mentioned	
Nozawa (32)	Japan	Case series	Scott wiring	20	30.00 (14/6)	23.7 (12-37)	42 (15.6-103.2)	0	Not provided	Sport	baseball, tennis, golf
Lundin (36)	USA	Case series	Morscher method	5	80.00 (1/4)	16.2 (15-18)	(30-78)	2, 40.00	Not provided	Not mentioned	adolescent swimmer
Ranawat (38)	UK	Case series	Buck repair	10	Not provided	20.8 (18-31)	68 (22-120)	Not provided	Not provided	Sport	professional cricketers
Debnath (39)	UK	Case series	Buck repair	19	31.82 (15/7)	20.2 (15-34)	Not provided	Not provided	Not provided	Sport	13 were professional footballers, four professional cricketers, three hockey players, one a tennis player and one a golfer
			Scott wiring	3							
Askar (41)	UK	Case series	Scott wiring	14	57.14 (6/8)	17.4 (13-24.8)	130.8 (96-180)	Not provided	Not provided	Not mentioned	
Ivanic (43)	Austria	Case series	Morscher method	113	30.97 (78/35)	16.5 (7.5-39)	130.8 (12-186)	107, 94.69	Not provided	Not mentioned	
Roca (44)	Spain	Case series	PS with hook	19	36.84 (12/7)	20.5 (13-29)	30 (24-48)	Not provided	Not provided	Not mentioned	
Schlenzka (45)	Finland	Case series	Scott wiring	25	64.00 (9/16)	18.2	14.8 (11-16)	Not provided	Not provided	Not mentioned	
Ogawa (33)	Japan	Case series	Scott wiring	7	28.57 (5/2)	26.7 (19-37)	51 (24-107)	0	Not provided	Sport	(rugby, volleyball, baseball, golf, or tennis
Debusscher (46)	Belgium	Case series	PS with hook	23	34.78 (15/8)	34 (16-52)	59 (6-113)	12, 52.17	Not provided	Not mentioned	
Noggle (37)	USA	Case series	MIS PS with rod/hook	5	20.00 (4/1)	15.8 (15-17)	7.2 (6-9)	0	116.4(60-180)	Mixed	pediatric farmer, athlete
Brennan (11)	USA	Case report	MIS Buck repair	1	100 (0/1)	17	6	0	Not provided	Sport	Baseball
Pai (47)	New Zealand	Case series	Scott wiring	5	25.00(15/5)	23(16-56)	7.35(5-11)	3, 15.00	Not provided	Mixed	three national or state level sportsmen, seven students who were competitive rugby or soccer players, five who were involved in a heavy manual job and five sedentary workers
			PS with wiring	15							

Table 1 (cont). *Baseline characteristics of included studies.*

References	Country	Study Design	Type of Surgery	Overall cohort							
				Patient Number	Gender: Women% (Men/ Women)	Mean Age (Range)	Follow-up (Months)	Associated Spondylolisthesis (n, %)	Mean Operation Time (Minutes)	Patient Population	Detail
Rajasekaran (48)	Indian	Case series	Buck repair	9	33.33 (6/3)	24 (15-31)	45 (9-108)	2, 22.22	58 (45-75)	Not mentioned	
Giudici (49)	Italy	Retro-spective cohort	Buck repair	7	35.48 (40/22)	18 (10-26)	108 (24-180)	52, 100	Not provided	Not mentioned	
			Scott wiring	8							
			PS with wiring	37							
Altaf (40)	UK	Case series	PS with rod	20	40.00 (12/8)	13.9 (9-21)	48 (27.6-87.6)	9, 45.00	Not provided	Not mentioned	
Koptan (50)	Egypt	Case series	PS with wiring	5	70.00 (3/7)	16 (14-19)	54 (24-84)	3, 30.00	115 (105-150)	Not mentioned	after surgical correction of their idiopathic scoliosis.
			PS with rod	5							
Eldin (12)	Egypt	Case series	MIS PS with rod	2	0 (2/0)	27 (25,29)	12	1, 50.00	125 (120,130)	Not mentioned	
Shin (51)	Seoul	Retro-spective cohort	Buck repair	15	Not provided	32 (26-42)	28 (24-36)	0	141.7 (135-175)	Not mentioned	
			PS with hook	23		38 (24-48)	37 (30-52)	0	174.9 (157-220)		
Kim (52)	Seoul	Case series	Buck repair	25	20.00 (20/5)	21 (15-29)	71 (36-123)	0	Not provided	Nonsport	no professional athletes or heavy physical workers.
Hioki (53)	Japan	Case series	Scott wiring	44	25.00(33/11)	24.2	85	0	Not provided	Sport	baseball in 8 cases, golf in 7 cases, and football and tennis in 5 cases each, snowboarding and bicycle racing in 3 cases each, basketball, swimming, jogging, and walking in 2 cases each, and karate, badminton, softball, field athlete, and mountaineering in 1 case each.
Widi (13)	USA	Case report	MIS Buck repair w/ BMP	3	Not provided	20.7 (17-25)	8.7 (7-12)	Not provided	Not provided	Mixed (67% athletes)	
Zhou (54)	China	Case series	PS with hook	22	13.64 (19/3)	18.4 (12-26)	25 (12-45)	Not provided	Not provided	Not mentioned	

Table 1 (cont). *Baseline characteristics of included studies.*

References	Country	Study Design	Type of Surgery	Overall cohort							
				Patient Number	Gender: Women% (Men/ Women)	Mean Age (Range)	Follow-up (Months)	Associated Spondylolisthesis (n, %)	Mean Operation Time (Minutes)	Patient Population	Detail
Takata (55)	Japan	Case series	MIS PS with rod/hook	10	20.00 (8/2)	32.8 (23-53)	16.1 (12-25)	1, 10.00	278 (205-326)	Not mentioned	
Snyder (56)	USA	Case series	Buck repair w/ BMP	16	Not provided	Not provided Median:16 (11-30)	14.06 (12-26)	0	Not provided	Mixed (50% athletes)	
Menga (57)	USA	Case series	Buck repair	31	54.84 (14/17)	16 (10-37)	60 (24-135)	2, 6.45	Not provided	Mixed (81% athletes)	
de Bodman (58)	France	Case series	Buck repair	35	48.57 (18/17)	13.7 (7-19)	112.8 (24-288)	35, 100	Not provided	Not mentioned	
Pu (59)	China	Case series	PS with rod	32	0 (32/0)	22 (19-32)	14 (12-24)	Not provided	85 (80-120)	Not mentioned	
Gillis (16)	USA	Case series	MIS Buck repair	8	Not provided	(16-23) except one 46 y/o	(12-44)	0	127	Sport	football, volleyball, track, hockey, national guard
Zhu (20)	China	Case series	Buck repair w/ navigation & microendoscopic technique	11	36.36(7/4)	28.4 (19-47)	15.7 (10-23)	0	147.6(126-183)	Not mentioned	
Karatas (17)	USA	Retrospective cohort	MIS Buck repair	9	44.44(5/4)	15.8 (13-17)	21	1, 11.11	151±35.0	Sport	
			PS with rod and hook, BMP	7	42.86(4/3)	16.4 (14-18)	24	1, 14.29	198±14.7	Sport	
Ghobrial (15)	USA	Case series	MIS Buck repair w/ BMP	9	33.33(6/3)	17.7 (14-20)	30.8 (2-59)	0	189±29	Sport	
Bartochowski (60)	Poland	Case series	Buck repair	5	0(5/0)	(13-18)	Not provided	Not provided	Not provided	Sport	soccer
Raudenbush (61)	USA	Case series	PS with hook	9	66.67(3/6)	15.4 (13-17)	11.9 (6-24)	2, 22.22	Not provided	Sport	dance, football, wrestling, gymnastics, softball, track, basketball

Table 1 (cont). *Baseline characteristics of included studies.*

References	Country	Study Design	Type of Surgery	Overall cohort							
				Patient Number	Gender: Women% (Men/ Women)	Mean Age (Range)	Follow-up (Months)	Associated Spondylolisthesis (n, %)	Mean Operation Time (Minutes)	Patient Population	Detail
Tian (19)	China	Case series	MIS Buck repair	23	21.74(18/5)	22.9(14-35)	24.2 (6-36)	0	97.8	Mixed	5 were students, 14 were manual workers, 2 were athletes, and 2 patients were office workers. This
Voisin (62)	Canada	Case report	PS with rod	1	0(1/0)	50	4	1, 100	120	Not mentioned	
Debnath (63)	UK	Case series	Scott wiring	3	66.67(1/2)	19 (8-30)	Not provided	0	Not provided	Mixed (94% athletes)	football (soccer) (22) followed by cricket (8), gymnastics (3), swimming (3), athletics (3), tennis (3), and others (10)
			Buck repair	44	25.00(33/11)						
Ishida (34)	Japan	Retro-spective cohort	PS with hook	5	60.00(2/3)	16(16-20)	22 (9-39)	Not provided	215	Not mentioned	
			PS with claw hook	13	7.69(12/1)	16(11-20)	12 (6-24)		271		
Tian (42)	China	Case report	MIS Buck repair	1	0(1/0)	26	6	0	Not provided	Not mentioned	
Mobbs (64)	Australia	Case report	Buck repair	1	100(0/1)	28	5	0	Not provided	Not mentioned	
Fayed (14)	USA	Case report	MIS Buck repair	2	100(0/2)	21.5 (21,22)	23 (21,25)	1, 50.00	Not provided	Mixed (50% athletes)	one track and softball
Takeuchi (35)	Japan	Case report	PS with rod	1	0(0/1)	29	12	0	174	Not mentioned	
Üçer (65)	Turkey	Case series	MIS Buck repair	18	44.44(10/8)	23.7(18-32)	16.04(12-28)	2, 11.11	40	Mixed	
Soliman (73)	Egypt	Case series	Endoscopic buck repair	7	28.6 (5/2)	21 (16-28)	21	0	65 (55-80)	Mixed (57% athletes)	Professional tennis player (2), gymnastic player (1), football player (1)

gical techniques comparable since the first minimally invasive technique was reported in 2003. Most studies were reported from Japan (31-35), the United States (11,14,36,37), the United Kingdom (38-41), and China (19,42). The number of included patients across the studies for which data were evaluated ranged from one to 113. Forty studies were included in the final analysis, with mean ages between 13.7 and 38 years. All were observational studies involving a total of 825 predominantly male patients. Risk of bias assessment has been included in the supplementary material. Most studies have a Newcastle-Ottawa Scale of more than 4/6. Table 2 summarizes the outcomes of different procedures for the meta-analysis.

Union Rate

Among the studies reporting union rates, 6 involved Scott wiring and 13 involved pedicle screw repair. Seventeen studies involved Buck repair, including 11 involving minimally invasive or endoscopic surgery. Three studies used the Morscher method. The union rates ranked from high to low were pedicle screw repair (effect size (ES) 95%; 95% CI, 86% to 100%), Buck repair (ES 93%; 95% CI, 86% to 98%), Scott wiring (ES 85%; 95% CI, 63% to 99%) and Morscher method (ES 63%; 95% CI, 2% to 100%), with the *P* value for heterogeneity between groups not reaching statistical significance (*P* = 0.759) (Fig. 3).

Reported Complications

Among the studies reporting complications, 9 involved Scott wiring and 14 involved pedicle screw repair. Twenty-three studies involved Buck repair, 12 involved minimally invasive or endoscopic methods, and 3 studies used the Morscher method. The complication rates were similar with Scott wiring (ES 12%;

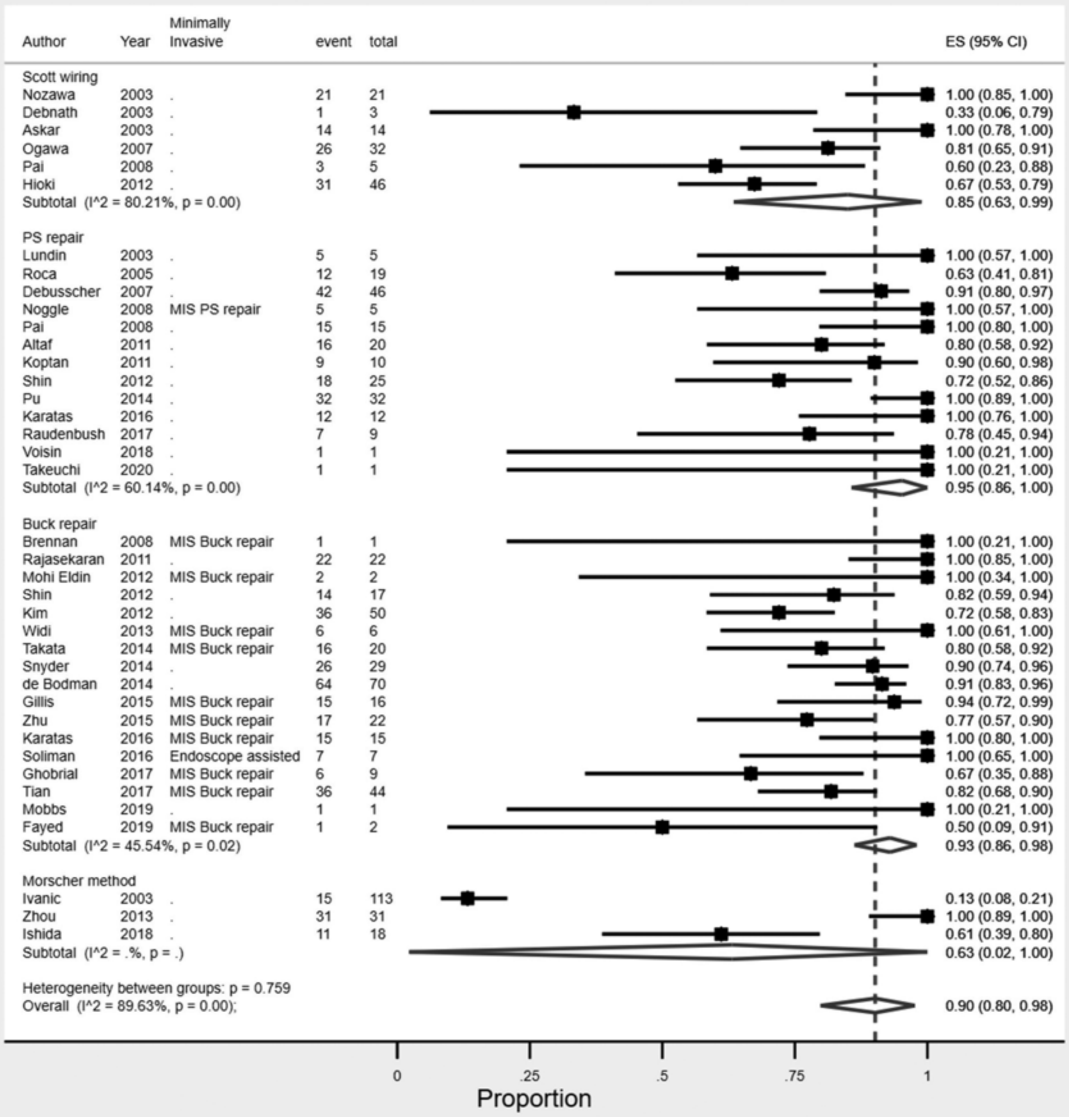

Fig. 3. *Forest plot comparing the union rates of different direct pars interarticularis repair techniques.*
ES, effect size; CI, confidence interval

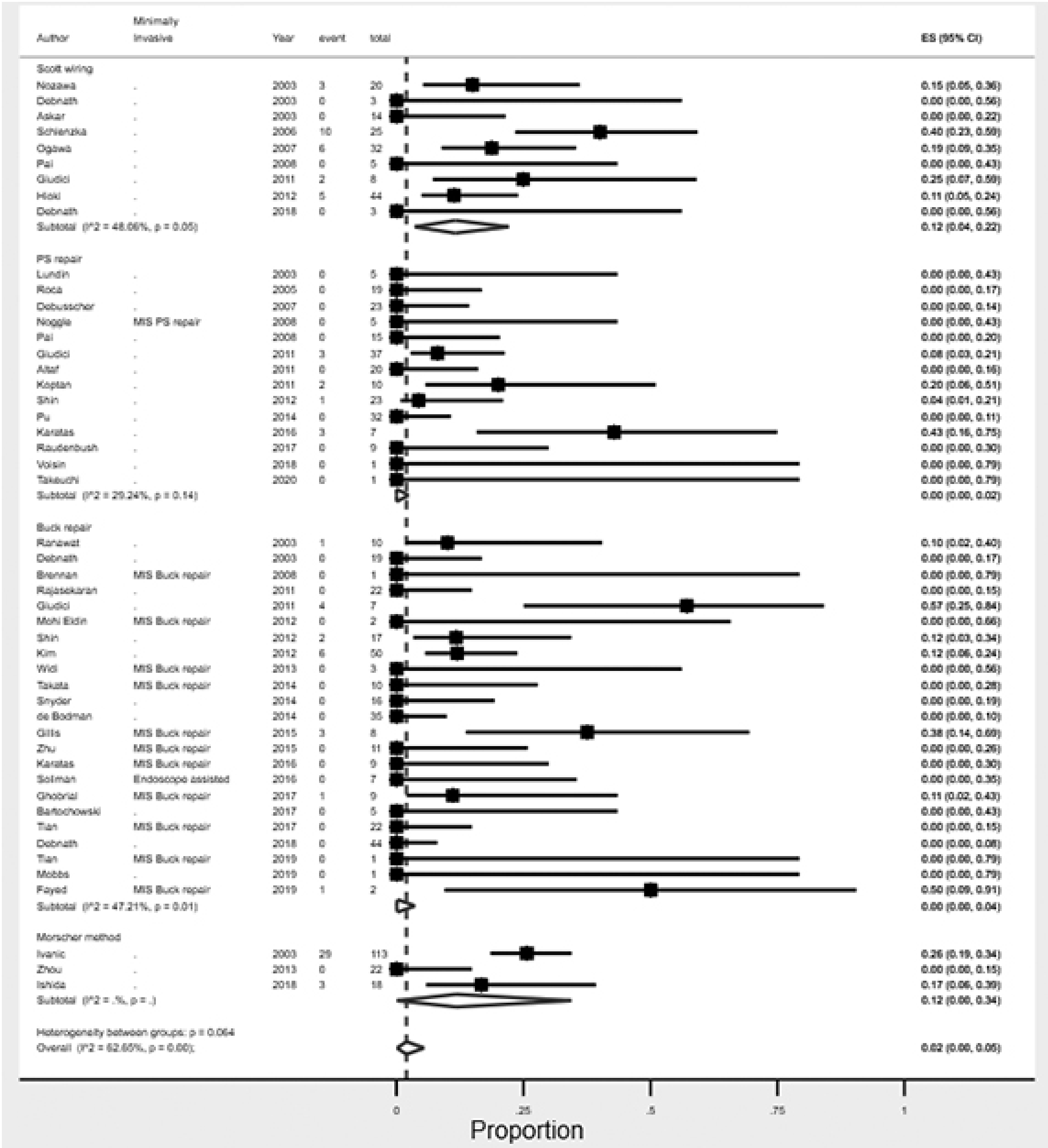

Fig. 4. ***Forest plot comparing the complication rates of different direct pars interarticularis repair techniques.***
ES, effect size; CI, confidence interval

95% CI, 4% to 22%) and the Morscher method (ES 12%; 95% CI, 0% to 34%). Both had complications higher than pedicle screw repair and Buck repair, with the *P* value for heterogeneity between the groups not reaching statistical significance (*P* = 0.064) (Fig. 4). The most reported complications between these 2 techniques were implant-related complications, including superficial wound infections, wire breakage, implant loosening, and persistent low back pain (10%, n = 15 in the Morscher method) (Table 3).

Implant Failure

Among studies reporting implant failure, 9 involved Scott wiring and 14 involved pedicle screw repair. Twenty-three studies involved Buck repair, 12 involved minimally invasive or endoscopic methods, and 3 studies used the Morscher method. The implant failure rates were similar for Scott wiring (ES 4%; 95% CI, 0% to 10%) and the Morscher method (ES 4%; 95% CI, 0% to 12%). However, both had higher implant failure rates than pedicle screw repair and Buck repair, with the *P* value reaching statistical significance for heterogeneity between the groups (*P* = 0.039) (Fig. 5). The Scott wiring technique had the highest wire breakage rate (9%, n = 12). The Morscher method had the highest implant loosening rate (5%, n = 7) (Table 3).

Wound Complications

Among the studies reporting wound complications, 9 involved Scott wiring and 14 involved pedicle screw repair. Furthermore, 23 studies involved Buck repair, while 12 used minimally invasive or endoscopic methods, and 3 used the Morscher method. The wound complication rate was highest using the Morscher method (ES 3%; 95% CI, 0% to 7%), with the *P* value for heterogeneity among the groups not reaching statistical significance (*P* = 0.353) (Fig. 6). Superficial wound infections were highest in the Morscher method (4%, n = 6) (Table 3). No deep infections were reported.

Positive Functional Outcome

Among the studies reporting positive functional outcome, 8 involved Scott wiring and 13 involved pedicle screw repair. Nineteen studies involved Buck repair, 10 used minimally invasive or endoscopic methods, and 3 studies used the Morscher method. The positive functional outcome rate was highest using the Morscher method (ES 3%; 95% CI, 0% to 7%), with the *P* value for heterogeneity between groups failing to reach statistical significance (*P* = 0.131) (Fig. 7). However, a high risk of bias has been reported by Ivanic (43), according to the GRADE assessment, due to a high reported positive functional outcome rate, compared to other studies.

Table 2. *Summary of union rates, complication rates, wound complication rates, implant failure rates, and positive functional outcomes rates for direct pars repair techniques.*

Direct Pars Repair Techniques	Study Number (n)	Patient Number (n)	Union Rates (95% CI)	Complication Rates (95% CI)	Wound Complication Rates (95% CI)	Implant Failure Rates (95% CI)	Positive Functional Outcome Rates (95% CI)
Buck repair	11	191	93% (82 to 100)	1% (0 to 7)	0% (0 to 0)	0% (0 to 0)	78% (46 to 99)
MIS Buck repair	12	107	92% (83 to 98)	0% (0 to 5)	0% (0 to 0)	0% (0 to 0)	91% (82 to 98)
Pedicle screw repair	14	207	95% (86 to 100)	0% (0 to 2)	0% (0 to 0)	0% (0 to 0)	84% (59 to 99)
Scott repair	9	129	85% (63 to 99)	12% (4 to 22)	0% (0 to 0)	4% (0 to 10)	80% (60 to 95)
Morscher method	3	153	63% (2 to 100)	12% (0 to 5)	3% (0 to 7)	4% (0 to 12)	91% (86 to 96)

n: numbers; CI: confidence interval; MIS: minimally invasive surgery

Table 3. *Specific complication rates of the direct pars repair technique.*

Specific Complications	Superficial Wound Infections (%, n)	Dural Tear (%, n)	Root Irritation (%, n)	Wire Breakage (%, n)	Implant Loosening (%, n)	Revision Surgery (%, n)	Donor Site Pain (%, n)	Persistent Low Back Pain (%, n)	Other* (%, n)
Buck repair	0% (0)	1% (1)	0% (0)	0% (0)	0% (0)	3% (6)	0% (0)	0% (0)	1% (2)
MIS Buck repair	0% (0)	0% (0)	1% (1)	0% (0)	1% (1)	1% (1)	0% (0)	1% (1)	0% (0)
Pedicle screw repair	1% (3)	0% (0)	1% (2)	0% (0)	0% (0)	1% (3)	0% (0)	0% (0)	0% (0)
Scott repair	1% (1)	0% (0)	2% (2)	9% (12)	1% (1)	2% (3)	0% (0)	0% (0)	2% (2)
Morscher method	4% (6)	1% (1)	1% (1)	0% (0)	5% (7)	1% (1)	0% (0)	10% (15)	0% (0)

n: numbers; MIS: minimally invasive surgery *Other complications included urinary tract infection (UTI), intraoperative drill breakage, pin breakage, transverse process fracture, and position failure of the hook.

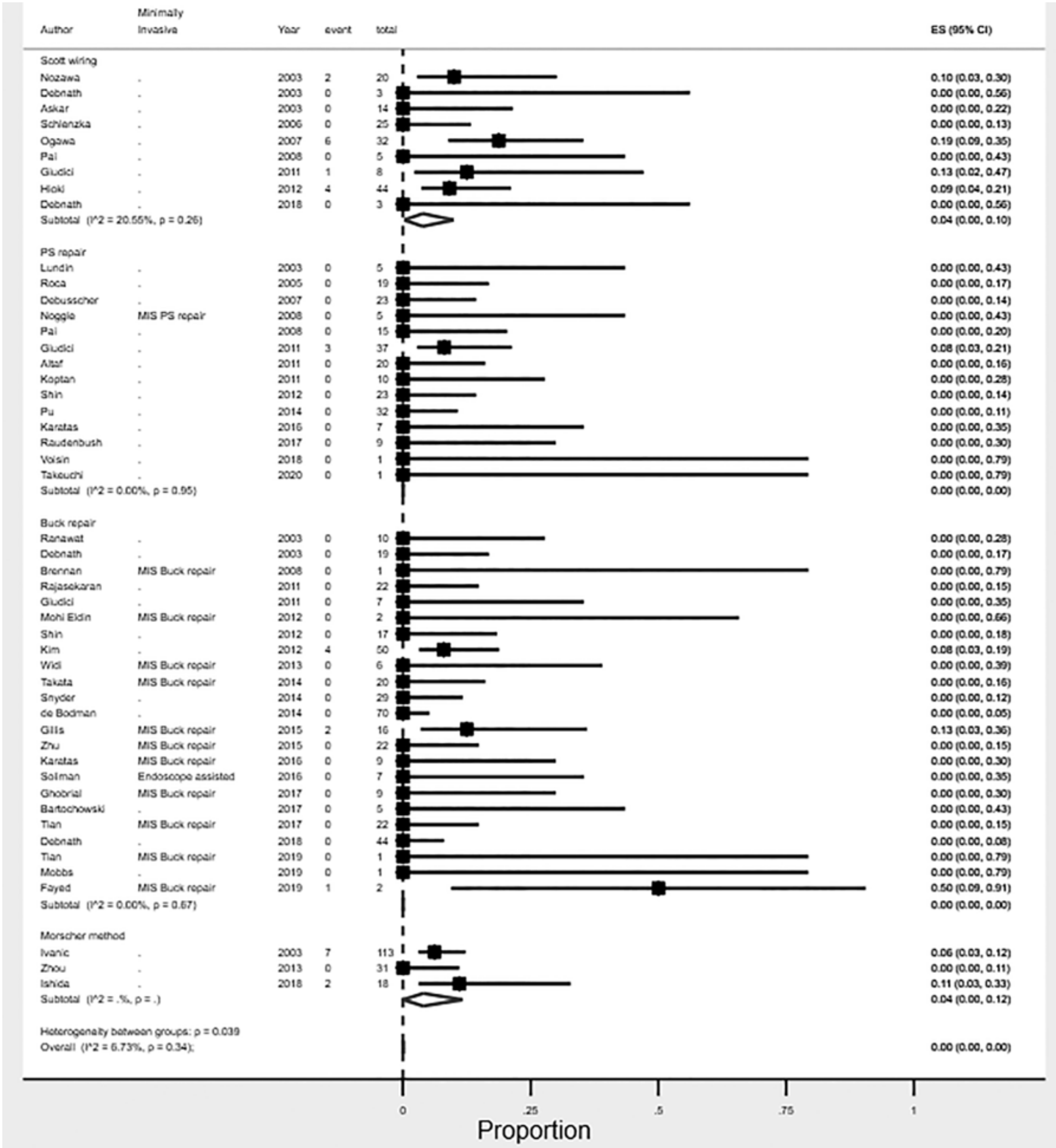

Fig. 5. *Forest plot comparing the implant failure rates of different direct pars interarticularis repair techniques.*
ES, effect size; CI, confidence interval

Sensitivity Analysis

The union rate analysis under exclusion of studies reporting 100% fusion rates showed higher fusion rates in the Buck repair group (ES 84%; 95% CI, 79% to 90%) and the pedicle screw repair group (ES 81%; 95% CI, 72% to 91%). After excluding all studies reporting no complications, higher complication rates were reported in the Scott wiring group (ES 20%; 95% CI, 10% to 29%) and the Morscher method group (ES 24%; 95% CI, 17% to 31%). Favorable functional outcome rates were higher in the Buck repair group (ES 84%; 95% CI, 77%to 92%) and the pedicle screw repair group

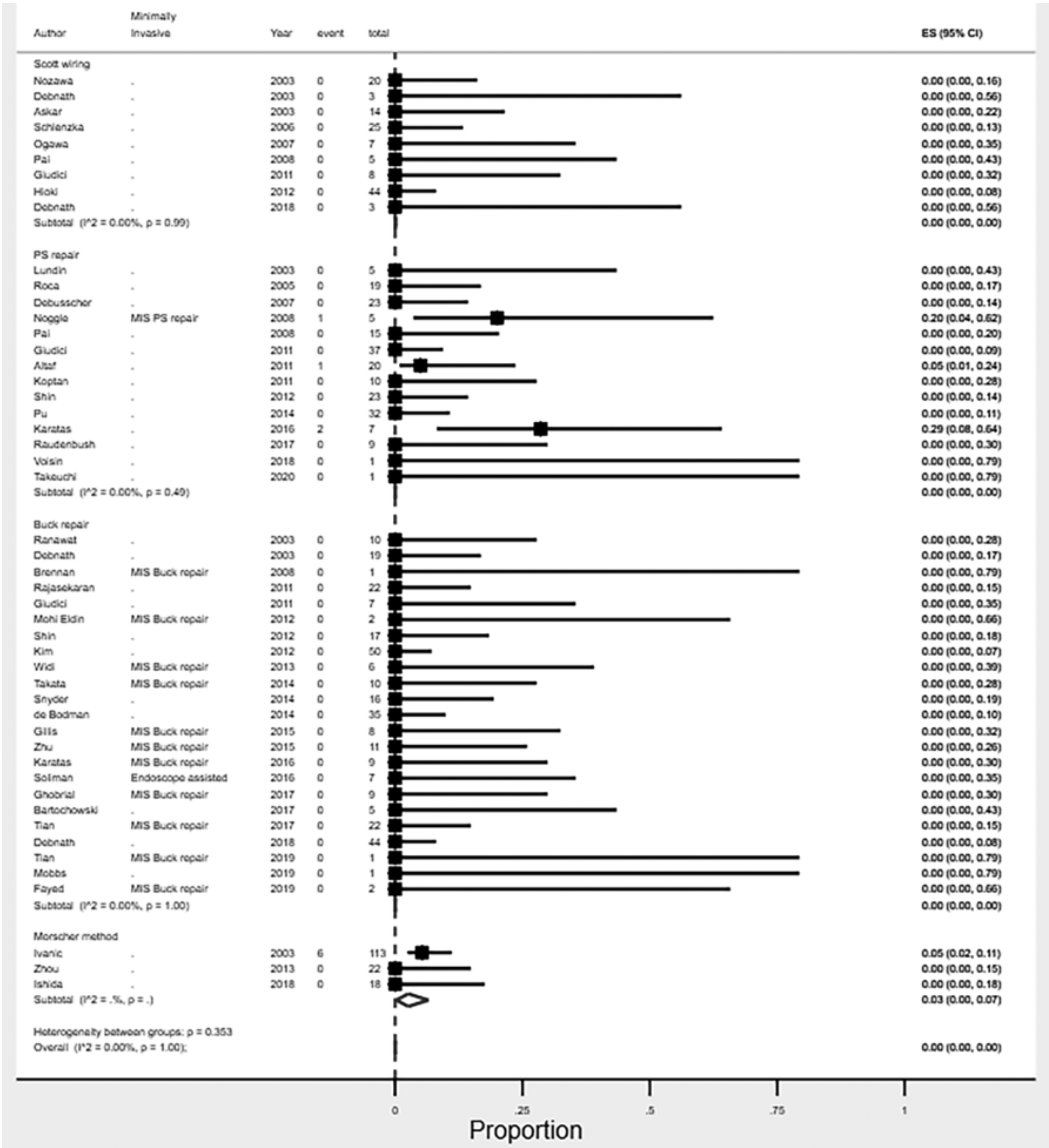

Fig. 6. ***Forest plot comparing the wound complication rates of different direct pars interarticularis repair techniques.***
ES, effect size; CI, confidence interval

(ES 87%; 95% CI, 81% to 92%), after excluding studies reporting 100% favorable functional outcome rates. These findings remained consistent under inclusion of studies with more than one year follow-up (Supplemental Material).

Subgroup Analysis

Minimally invasive procedures were compared to open procedures, demonstrating high union rates and low overall complication and implant failure rates. Higher positive functional outcome rates were re-

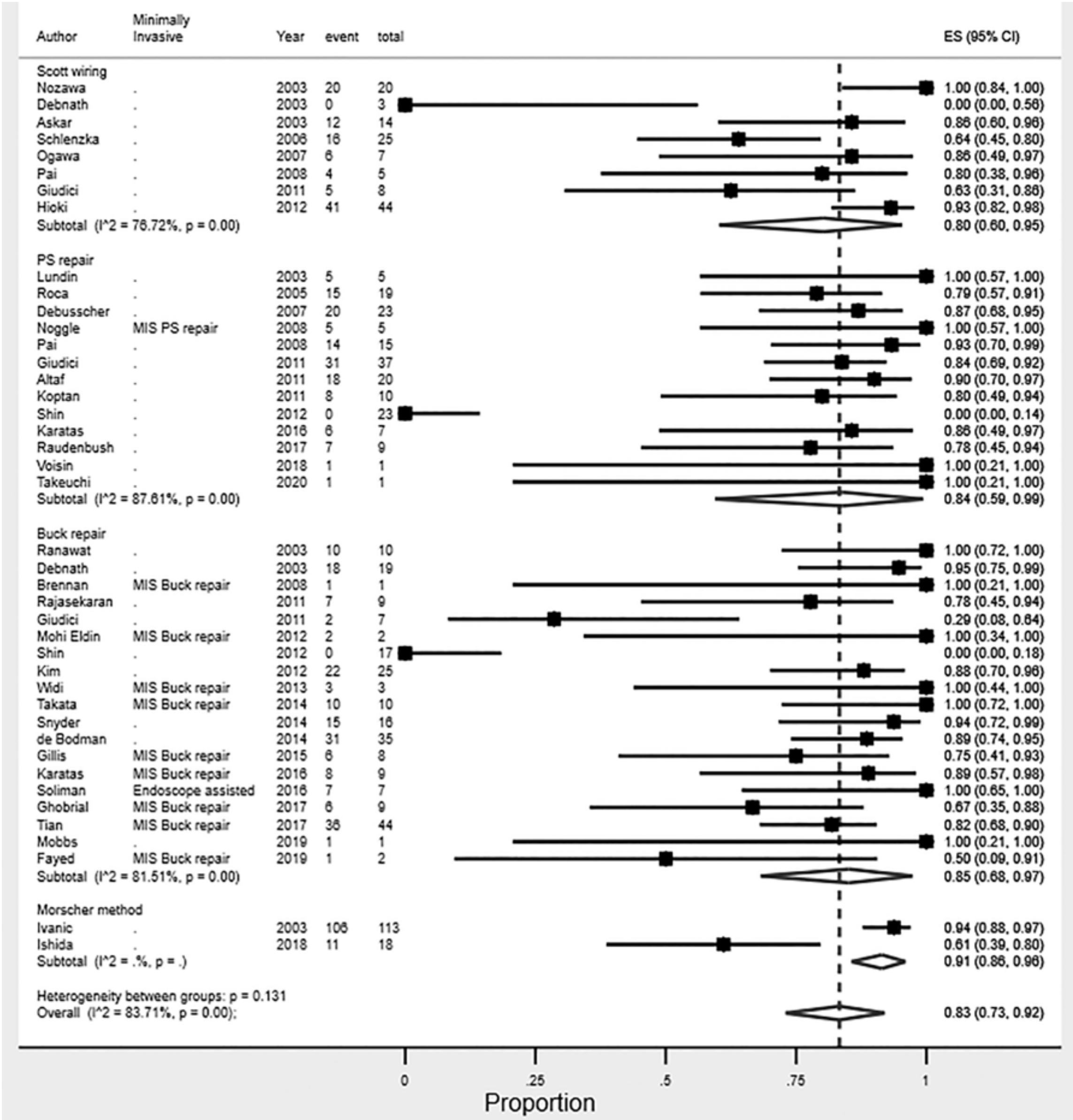

Fig. 7. ***Forest plot comparing the wound positive functional outcome rates of different direct pars interarticularis repair techniques.***
ES, effect size; CI, confidence interval

ported for minimally invasive surgery (MIS) Buck repair (ES 91%; 95% CI, 82% to 98%) versus conventional Buck repair (ES 78%; 95% CI, 46% to 99%) (Table 2 and Supplemental Material). Studies involving predominantly women and sporting populations were further analyzed, whereby both revealed high union rates and low complication rates among the pedicle screw repair and Buck repair groups (Supplemental Material).

Discussion

We evaluated the outcomes of direct pars interarticularis repair and found that union rates were higher in the pedicle screw repair and Buck repair group with lower complication rates, compared to the Scott repair and Morscher methods. Minimally invasive Buck repairs had positive functional outcomes compared to open repairs.

Buck repair is commonly used for direct repair of pars interarticularis. This method is reliable and relatively straightforward for most simple-type pars fractures. Traditionally, a 3.5-mm cortical screw is used for a unilateral L5 pars fracture (67). The fully threaded screw compresses the lamina while maintaining tension. A burr may be used on the inferior part of the lamina to create a "countersink" area to facilitate the screw head entering the drill hole. A flexible drill bit may be used for a cranial level lumbar spine to avoid the need to extend the caudal aspect of the incision while allowing the drill to achieve the correct trajectory in the sagittal plane. Most studies have reported reasonable union rates and low complication rates, which is similar to our findings among MIS buck repair and open Buck repair techniques (48,68). This may be due to the small wound incisions, the nature of natural bone-to-bone contact under direct screw compression, and the vital biomechanics of the repaired segment (68).

Pedicle screw repair has also shown high union rates compared to other methods. This technique may be helpful when the lytic defects are predominantly in the coronal plane. A pedicle screw with a hook or rod construct is commonly used (36). Deguchi et al (69) have shown promising biomechanical results with these constructs across the defects. This technique is also more familiar to most spine surgeons, which may explain the overall low complication rates from our findings, compared to the placement of pars interarticularis screws. Also, there is no loss of lumbar motion segments through the avoidance of segmental instrumentation such as traditional lumbar fusions.

Scott repair has a higher complication rate with low union rates compared to other techniques. The high complication rates might have been affected by the long follow-up of this technique from the collected studies. It usually involves a cerclage wire passing through the transverse processes and inferior edge of the spinous process with a tension-band effect (41). The fixation might be limited due to its reliance on the weak transverse processes as anchors (66,70). In addition, the wiring technique might not provide stabilization across lytic defects if there is a bifid spinous process or lamina (70). The procedure is also technically demanding, and larger wounds may be needed to perform the operation. A high wire breakage rate (9%) was noted from our findings.

High functional outcomes for the Morscher method were reported by Ivanic et al (43). However, after excluding this study from our sensitivity analysis, both the Buck repair and pedicle screw repair method had a higher pooled functional outcome than the Morscher method. This fixation method might be useful if a thin lamina is present and a 3.5-mm cortical screw is not feasible (43). A hook is placed under the inferior edge of the lamina, which can also guide the drilling of the superior facet and pedicle complex, keeping in mind that spina bifida occulta or lamina that is less than 4 mm thick have been suggested as contraindications for this procedure (34). The screw is inserted into the superior facet after tapping, and the hook is compressed with a threaded nut. This type of fracture fixation, however, has been associated with high persistent low back pain (10%) compared to other techniques.

Minimally Invasive Buck Repair and Endoscopic Decompression

The first minimally invasive technique was reported in 2003 by Sairo et al (31) They demonstrated a decompression technique under endoscope affected by pars interarticularis defects which had acceptable patient-reported outcomes. Üçer (65) published the latest study on minimally invasive Buck repair, where a single institutional experience of 18 patients was reported. Mean VAS scores for back pain were reduced from 6.93 preoperatively to 1.1 during the 12-month follow-up, decreasing gradually at each time point after surgery. A similar pattern was also detected for mean ODI with a significant drop from a baseline of 64.8 to 1.44 in the 12-month follow-up.

Comparison of Minimally Invasive Techniques to Conventional Techniques

Prior to the present meta-analysis, a review of the literature was presented by Raffa et al (71), summarizing the conventional and minimally invasive techniques for repairing isthmic pars interarticularis fractures. In an evaluation of all 4 techniques (Buck repair, Scott wiring, Morscher method, and pedicle screw-based repair), the authors concluded that all minimally invasive techniques are safe and have the potential to provide clinical benefit. Moreover, fluoroscopy-guided procedures with the addition of recombinant human bone morphogenetic protein were found to give additional advantage (71). A recent systematic review also studied a similar question in a specific population of athletes. For both MIS and conventional techniques, the most common approach was Buck repair. Compared to traditional methods, patients undergoing MIS were found to have higher rates of pain resolution ($P <$

0.001) with similar rates of complications and return to previous levels of activity (72). In our analysis, MIS Buck repair was also found to have good patient-reported outcomes with high union rates.

Limitations

Surgical treatment of patients with lumbar spondylolysis, specifically attempting the direct repair of pars lysis, has been reported in numerous case series and individual case studies, many, if not most, of which have been included in the current study.

The major limitation of this study was the potential heterogeneity among studies. This is associated with patient age, gender, lysis age, and unilateral versus bilateral lysis, among other factors. The current meta-analysis does not adequately address these risk modifying factors and how they vary among studies and patients. However, we have performed sensitivity analyses from the available data to address this issue in the supplementary material. Women and sports predominant populations produced similar results compared to the primary data. The wide range of follow-up times may affect efficacy and complications. The higher complication rates among the Morscher method and Scott wiring groups may have resulted from the longer follow-up. Furthermore, publication bias cannot be excluded in this systematic review, since studies with significant, positive results and those involving surgical treatment with commercial value are much more likely to be published. This effect is presented in our funnel plots in the supplementary material. Other limitations may be similar to those inherent with all meta-analyses, including studies missed during our search and unknown biases within the selected studies.

Conclusion

Our findings revealed that pedicle screw repair and Buck repair might be associated with a higher fusion rate and lower complication rates than the Scott repair and Morscher methods. Thus, minimally invasive techniques may provide enhanced positive functional outcomes for patients with spondylolysis. Ultimately, the choice of technique should be based on the invasive surgeon's preference and experience.

Author Contributions

This study was designed by SHLT and CWC. Data collection and analysis was performed by SHLT and WCC. All authors contributed to the preparation of the manuscript, review, and approval of the final version's content.

Supplemental material is available at painphysicianjournal.com

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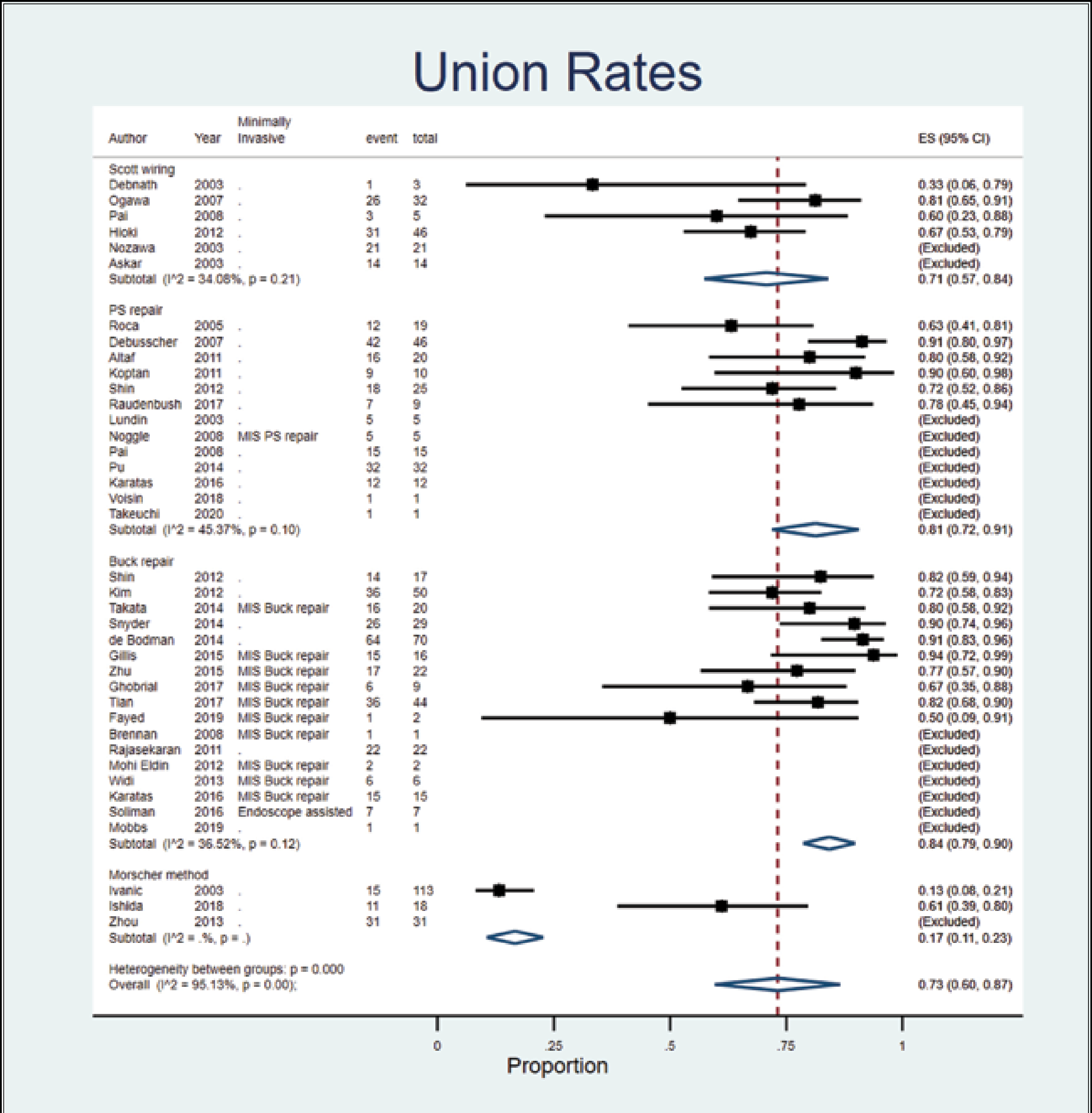
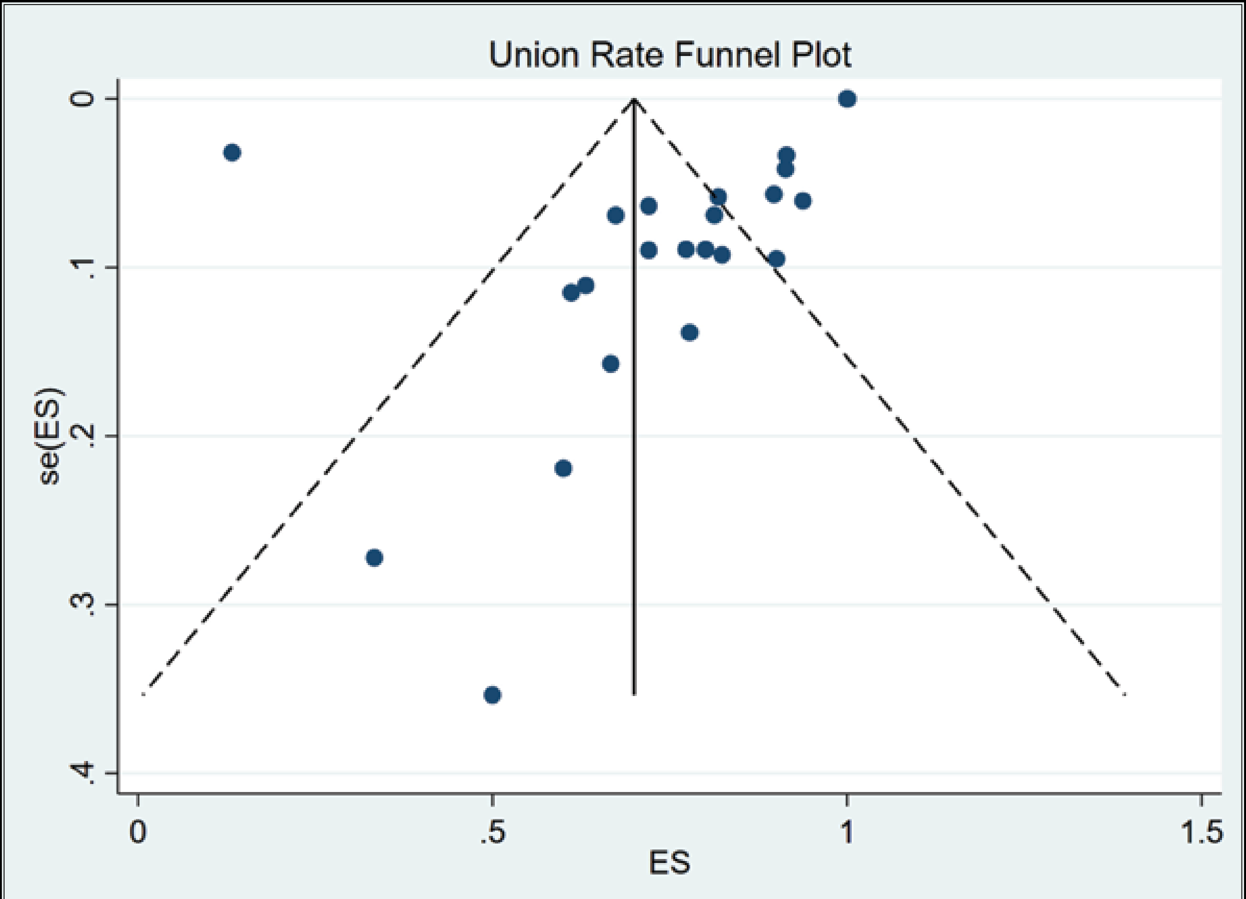
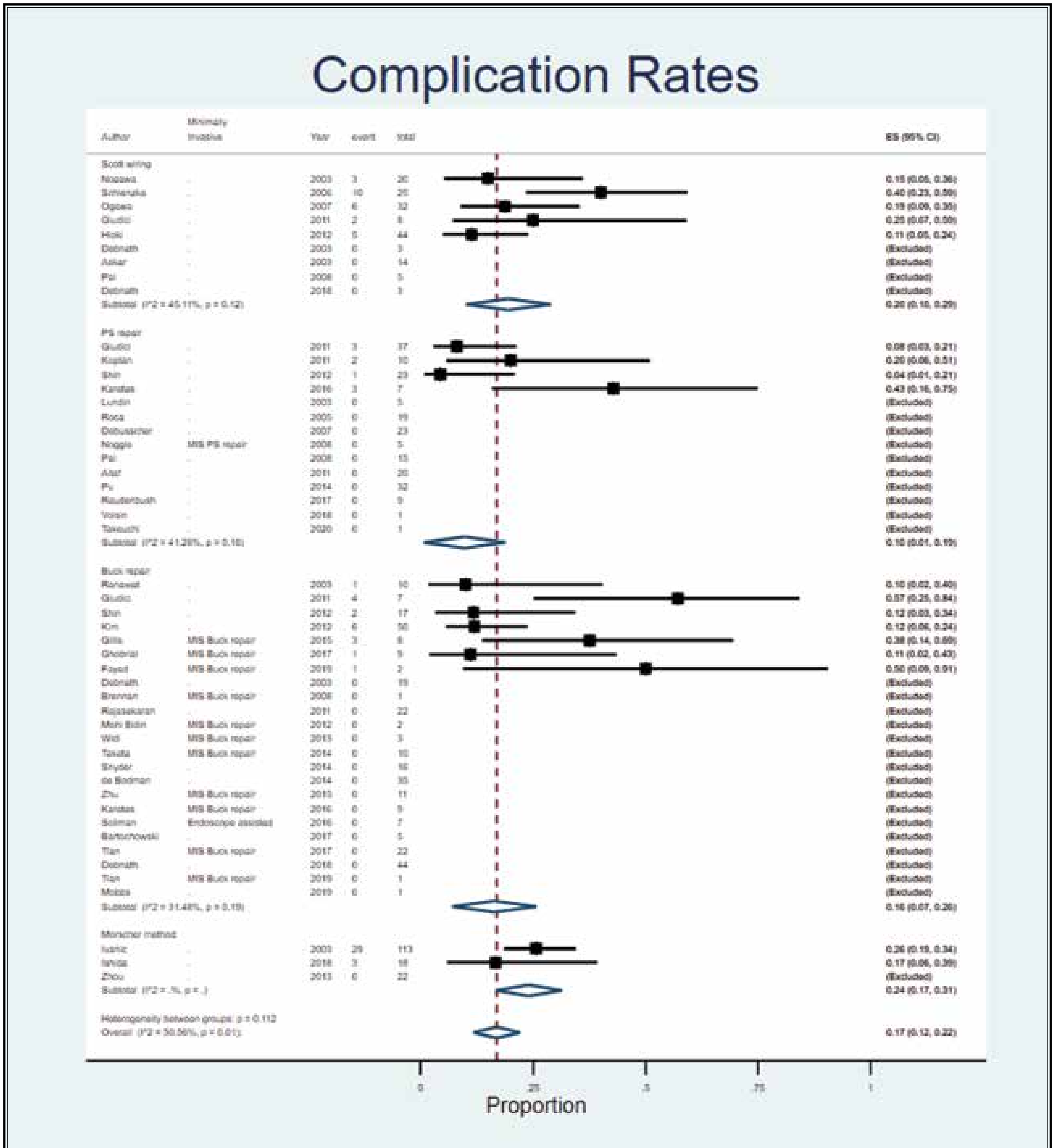


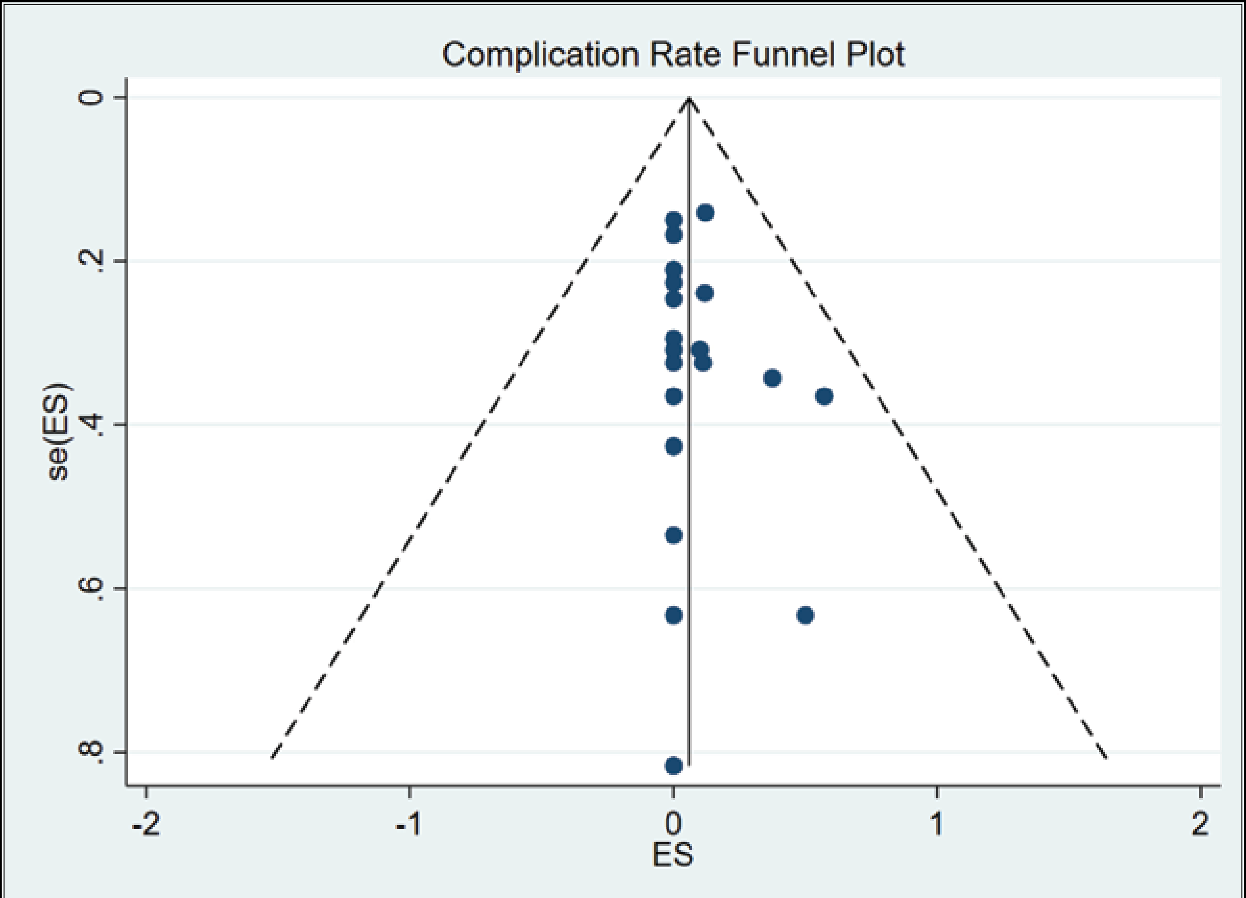
Supplemental Fig. 1. *Sensitivity analysis of union rates excluding articles reporting 100% union.*



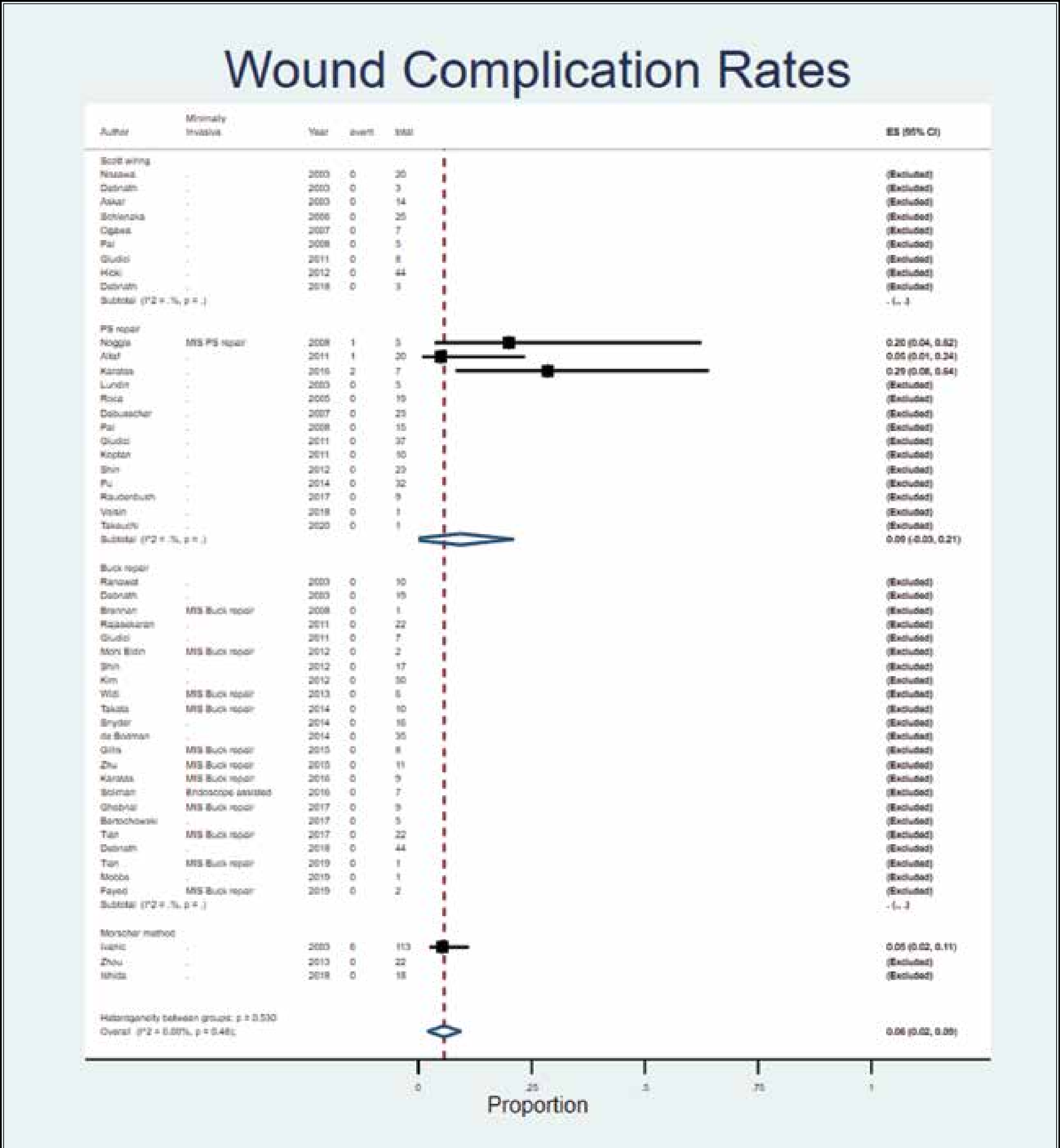
Supplemental Fig. 2. *Funnel plot identifying publication bias and small study effect, with Egger's test quantifying the significance in the excluded 100% union studies*



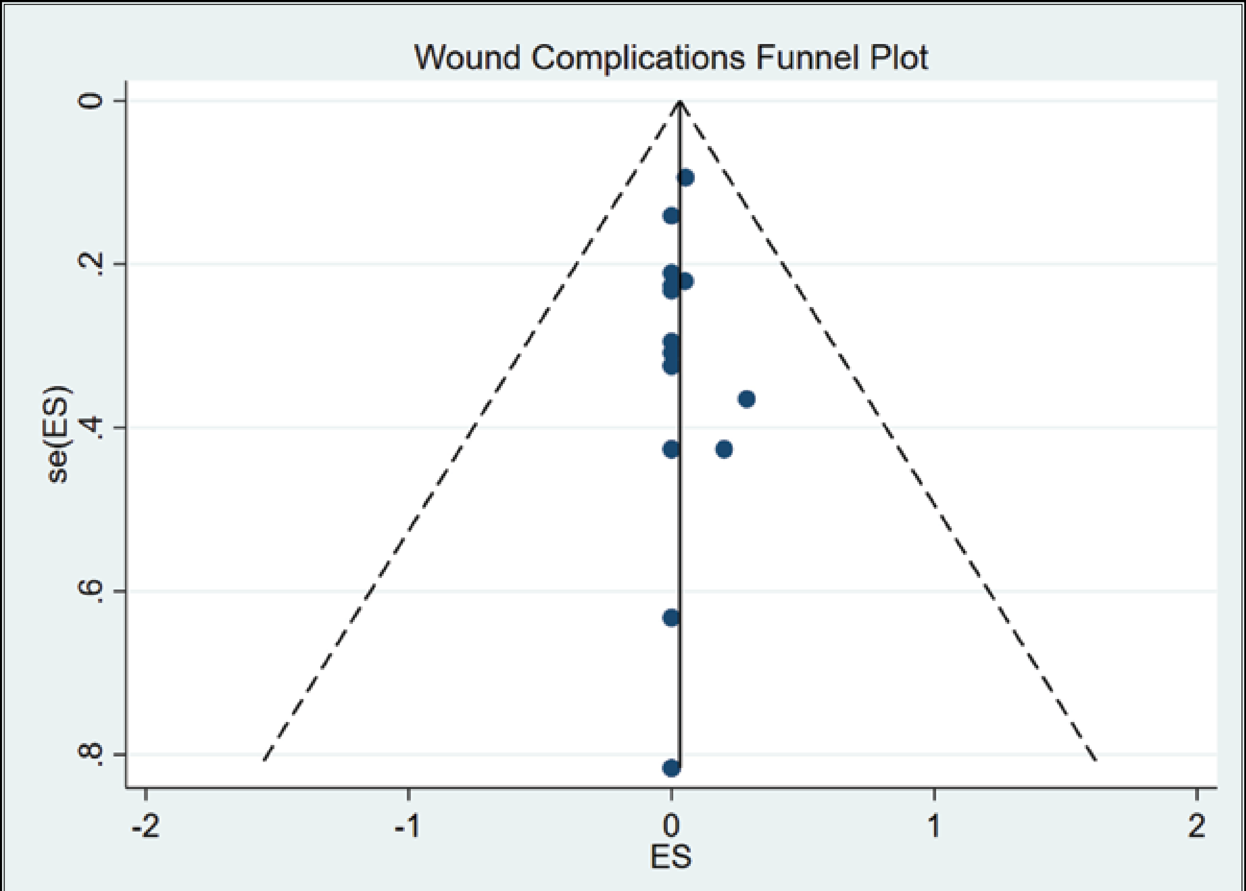
Supplemental Fig. 3. *Sensitivity analysis of complication rates excluding articles reporting no complications*.



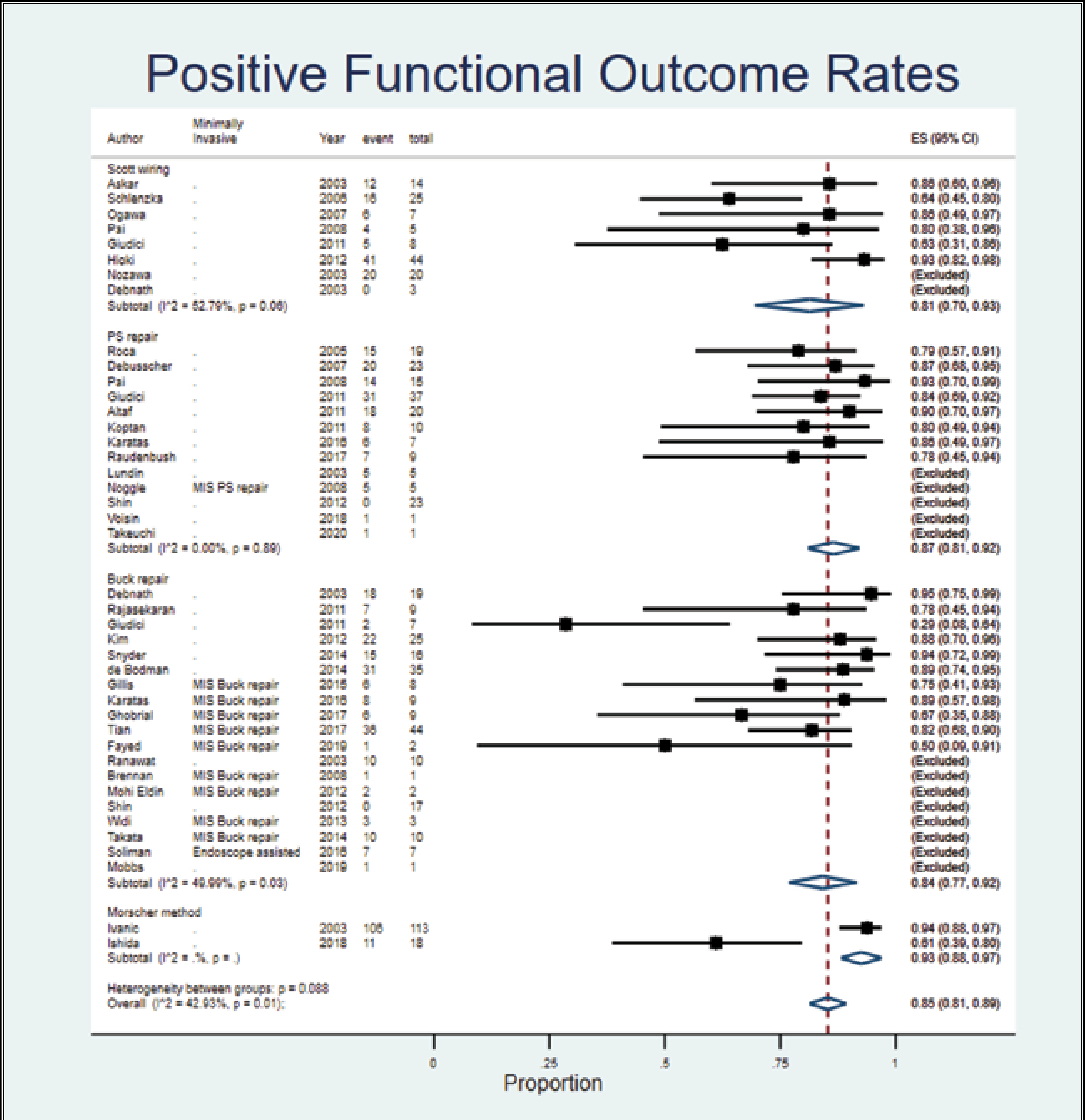
Supplemental Fig. 4. *Funnel plot identifying publication bias and small study effect, with Egger's test quantifying the significance in the excluded no complication studies*



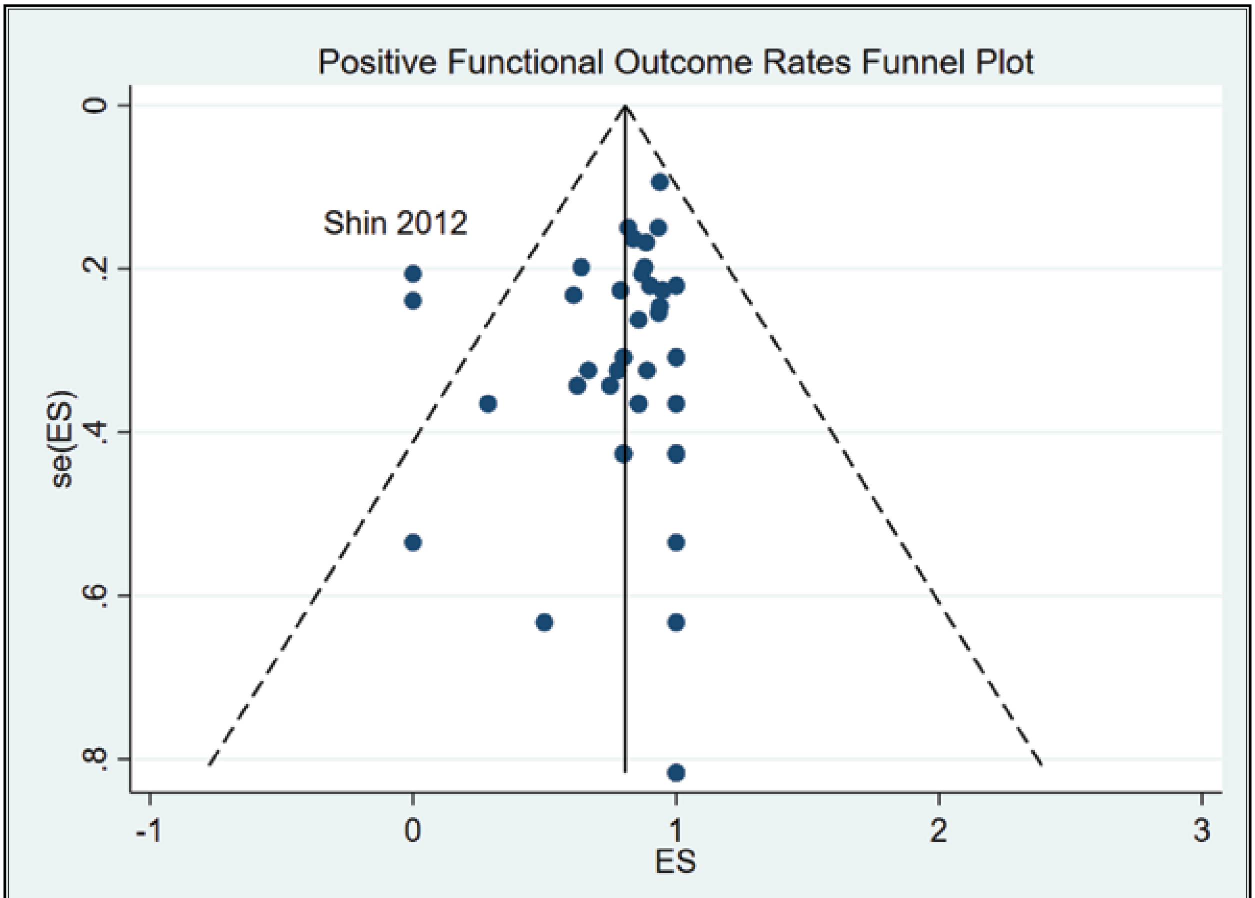
Supplemental Fig. 5. *Sensitivity analysis of complication rates excluding articles reporting no wound complications*



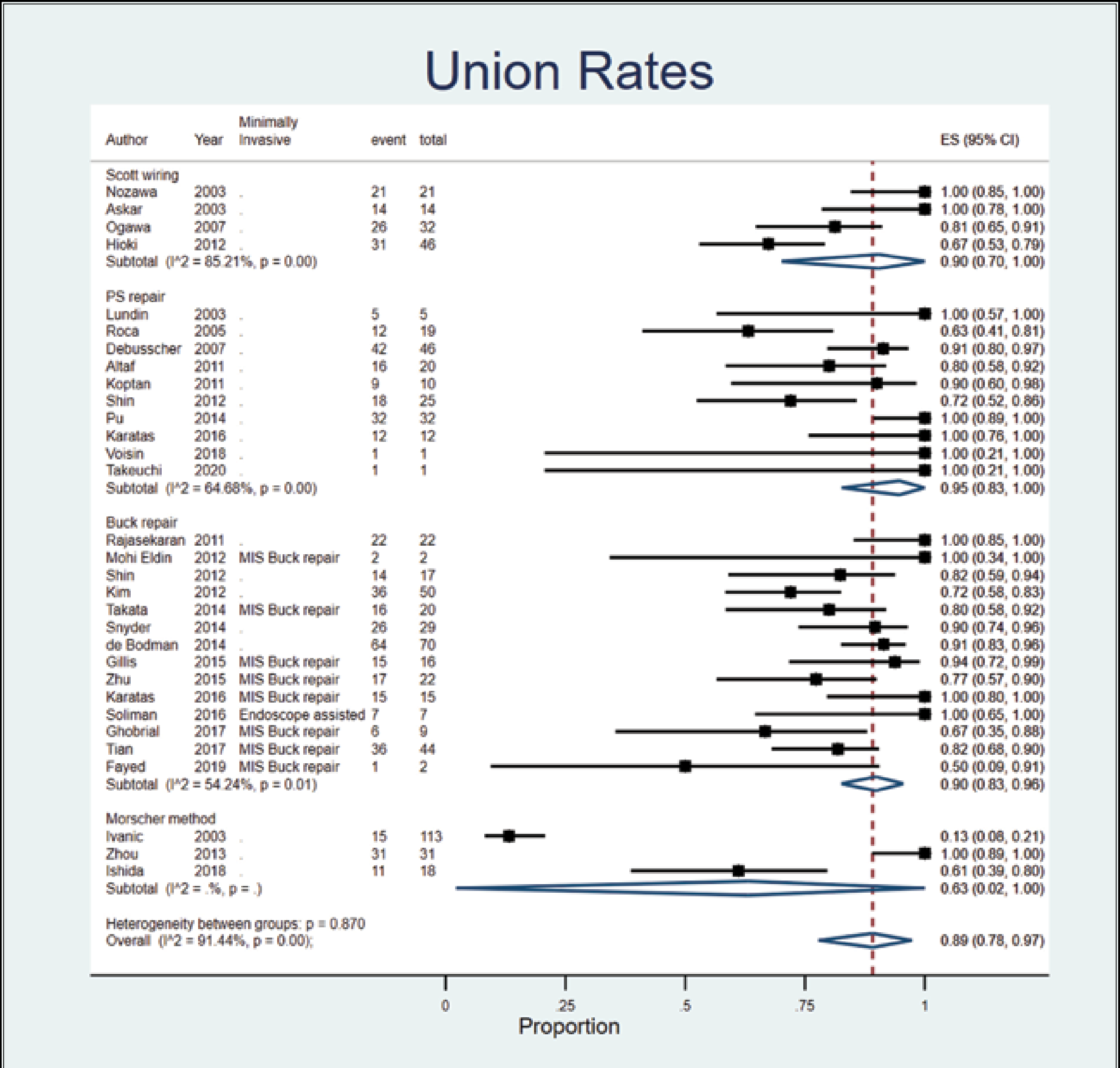
Supplemental Fig. 6. *Funnel plot identifying publication bias and small study effect, with Egger's test quantifying the significance in the excluded no wound complication studies*



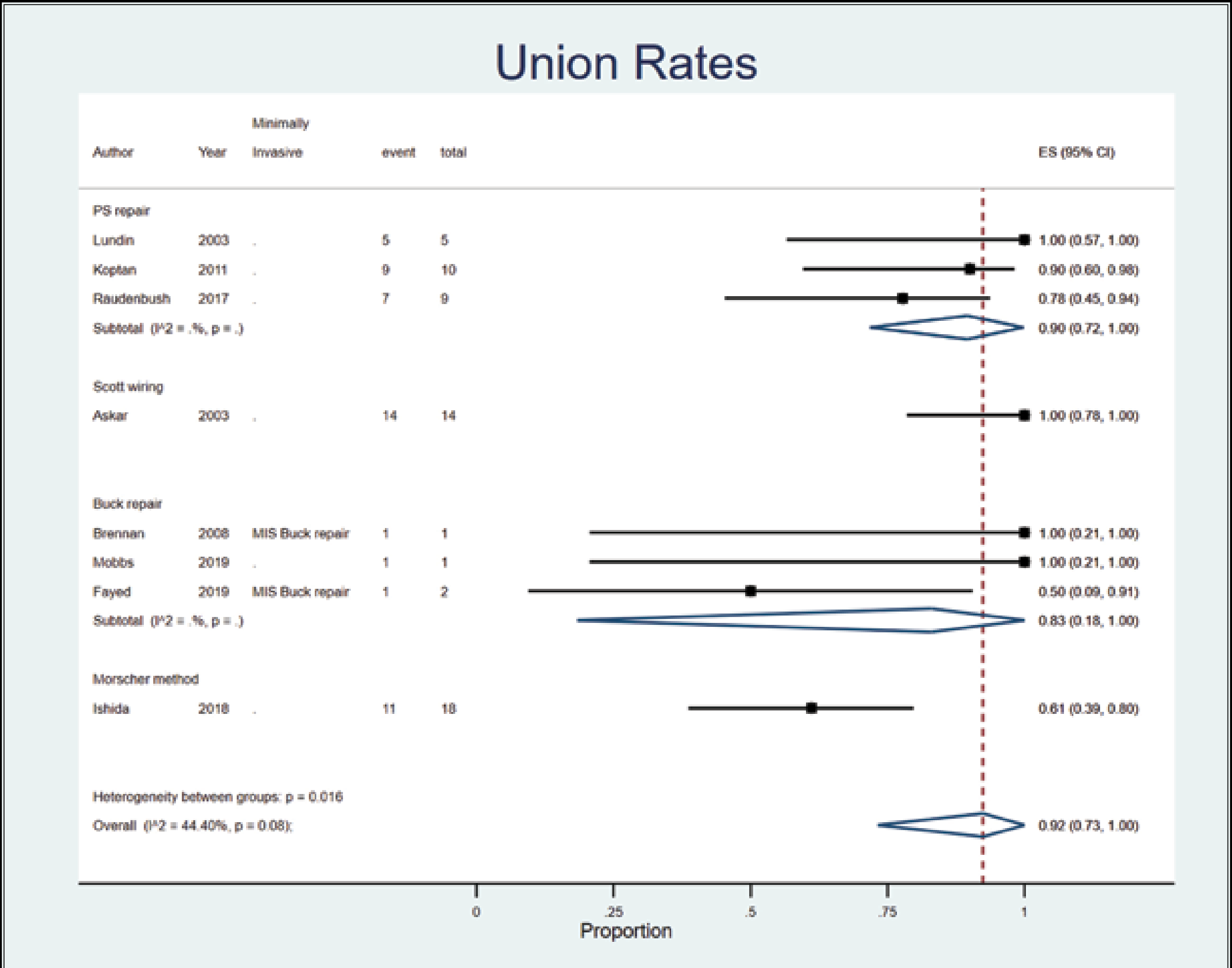
Supplemental Fig. 7. *Sensitivity analysis of complication rates excluding articles reporting 100% positive functional outcomes*



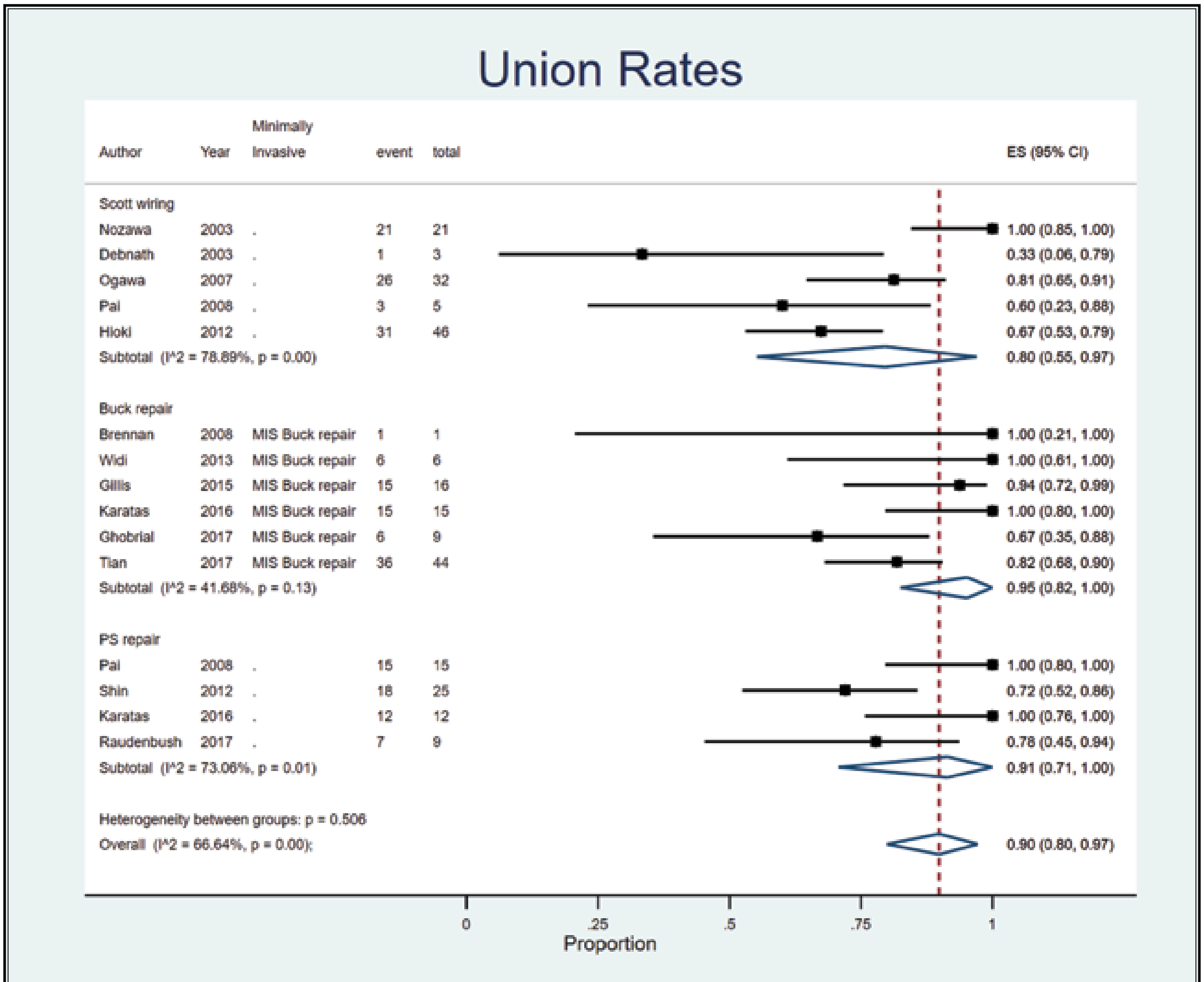
Supplemental Fig. 8. *Funnel plot identifying publciation bias and small study effect, with Egger's test quantifying the significance in the excluded 100% positive functional outcome studies*



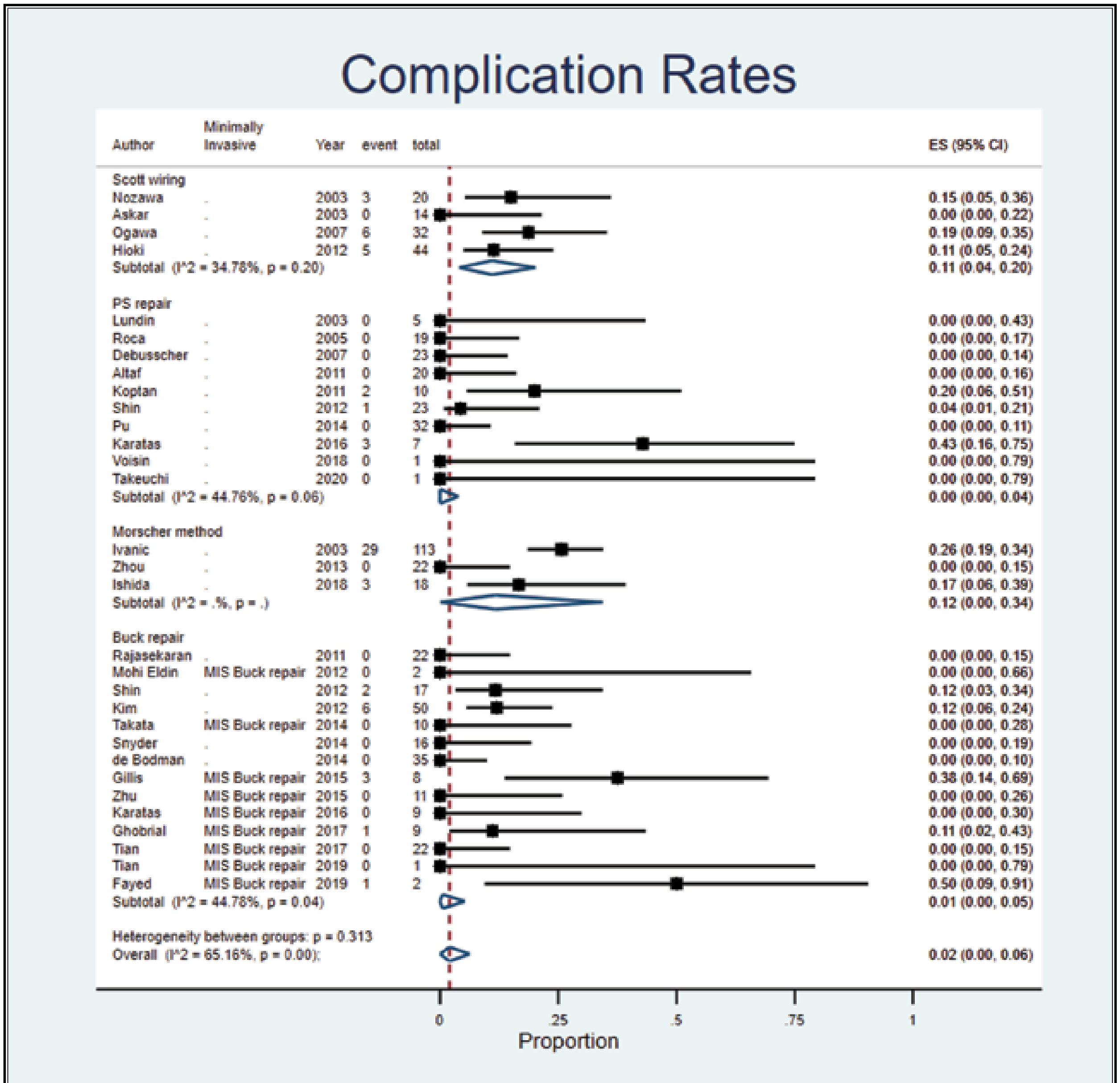
Supplemental Fig. 9. *Sensitivity analysis of union rates with studies followed up more than 1 year*



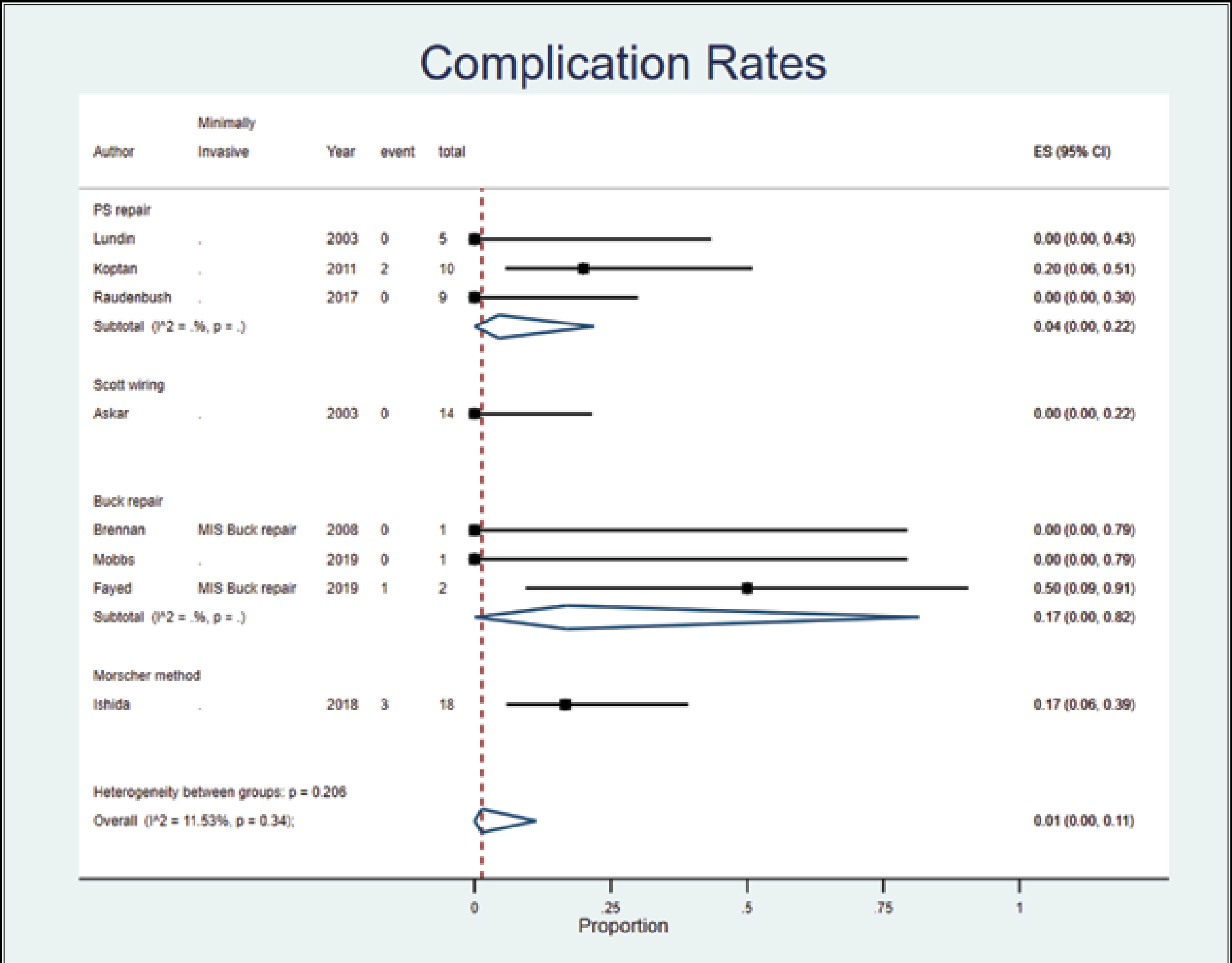
Supplemental Fig. 10. *Subgroup analysis of union rates in female-predominant studies*



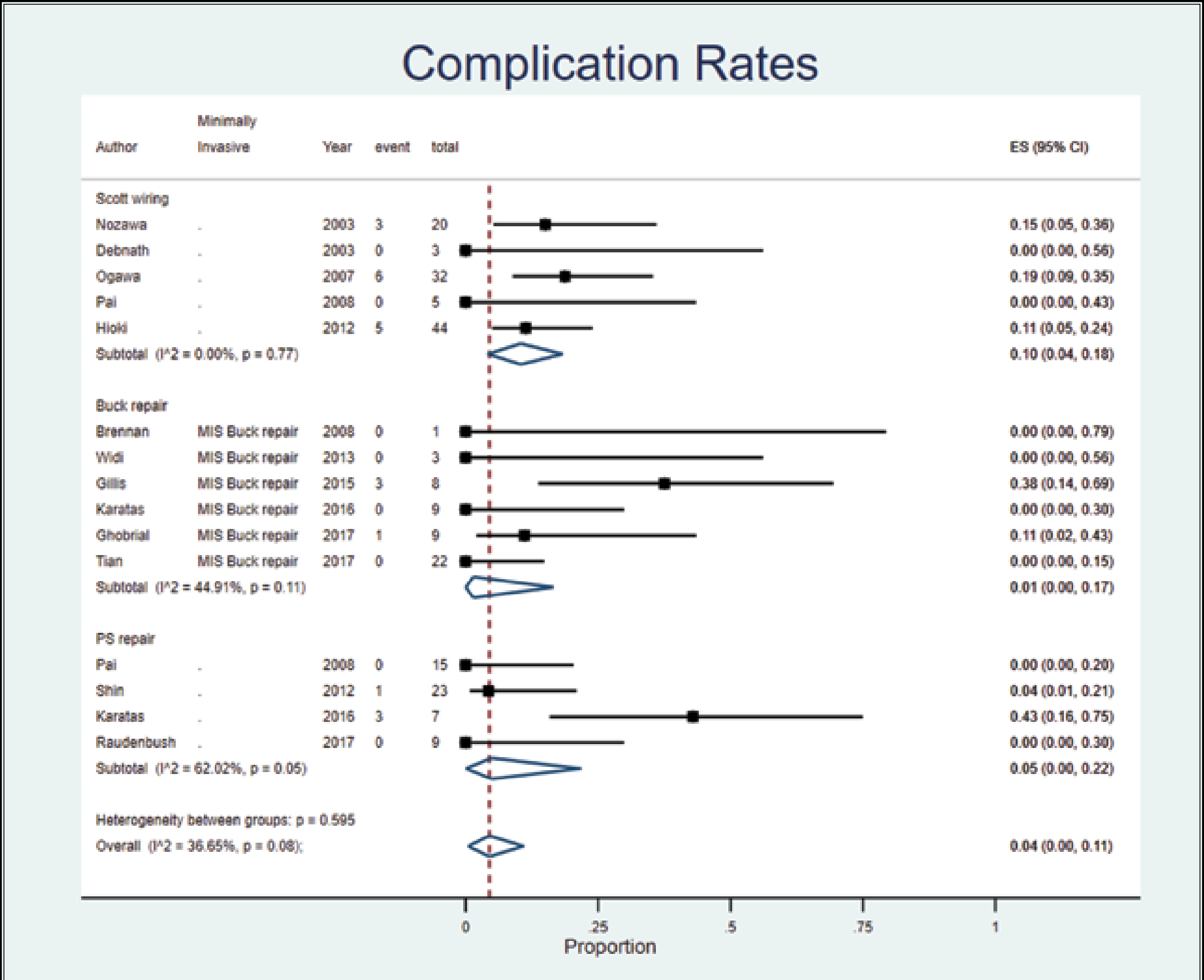
Supplemental Fig. 11. *Subgroup analysis of union rates in sport population studies*



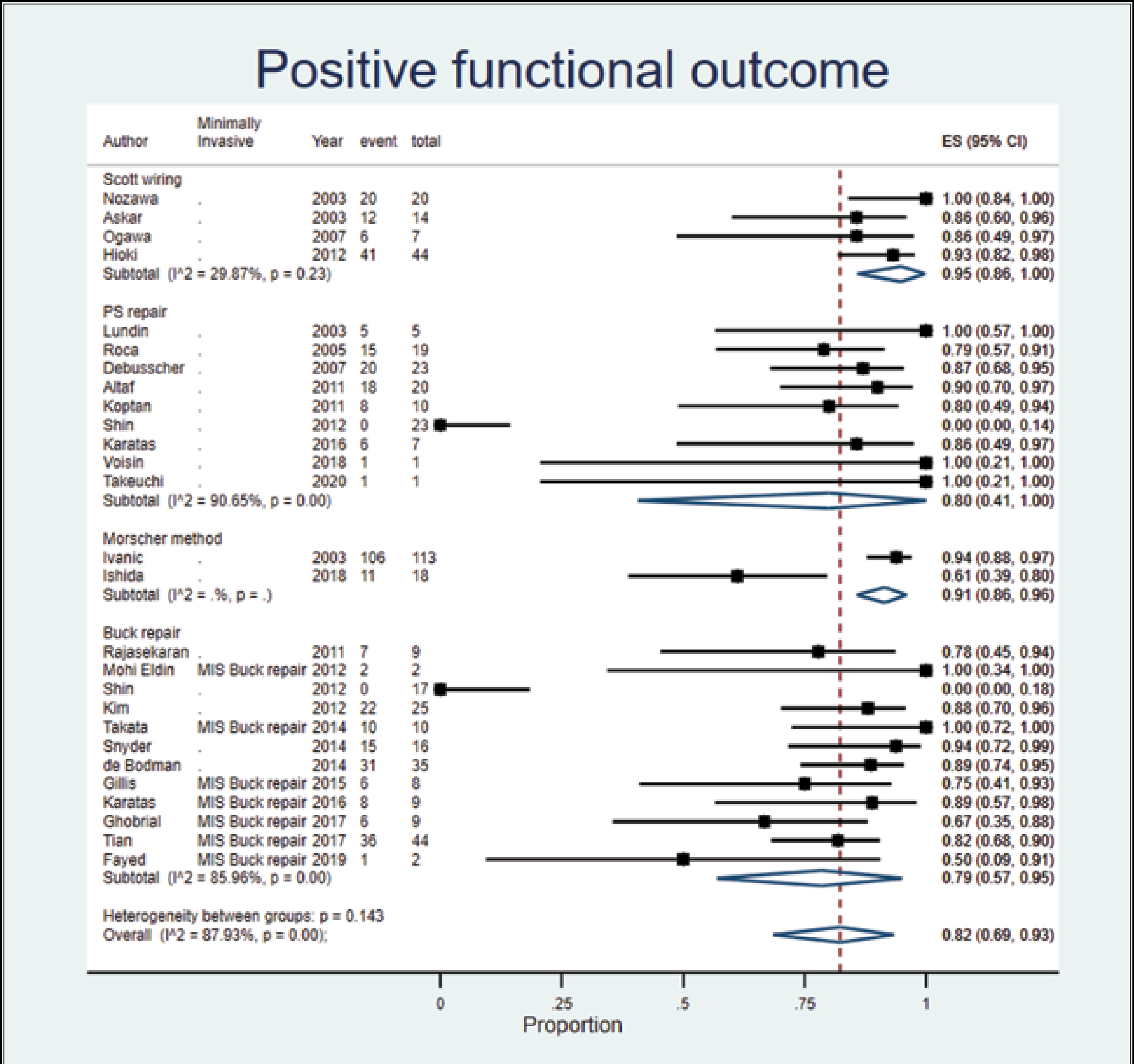
Supplemental Fig. 12. *Sensitivity analysis of complication rates with studies followed up more than 1 year*



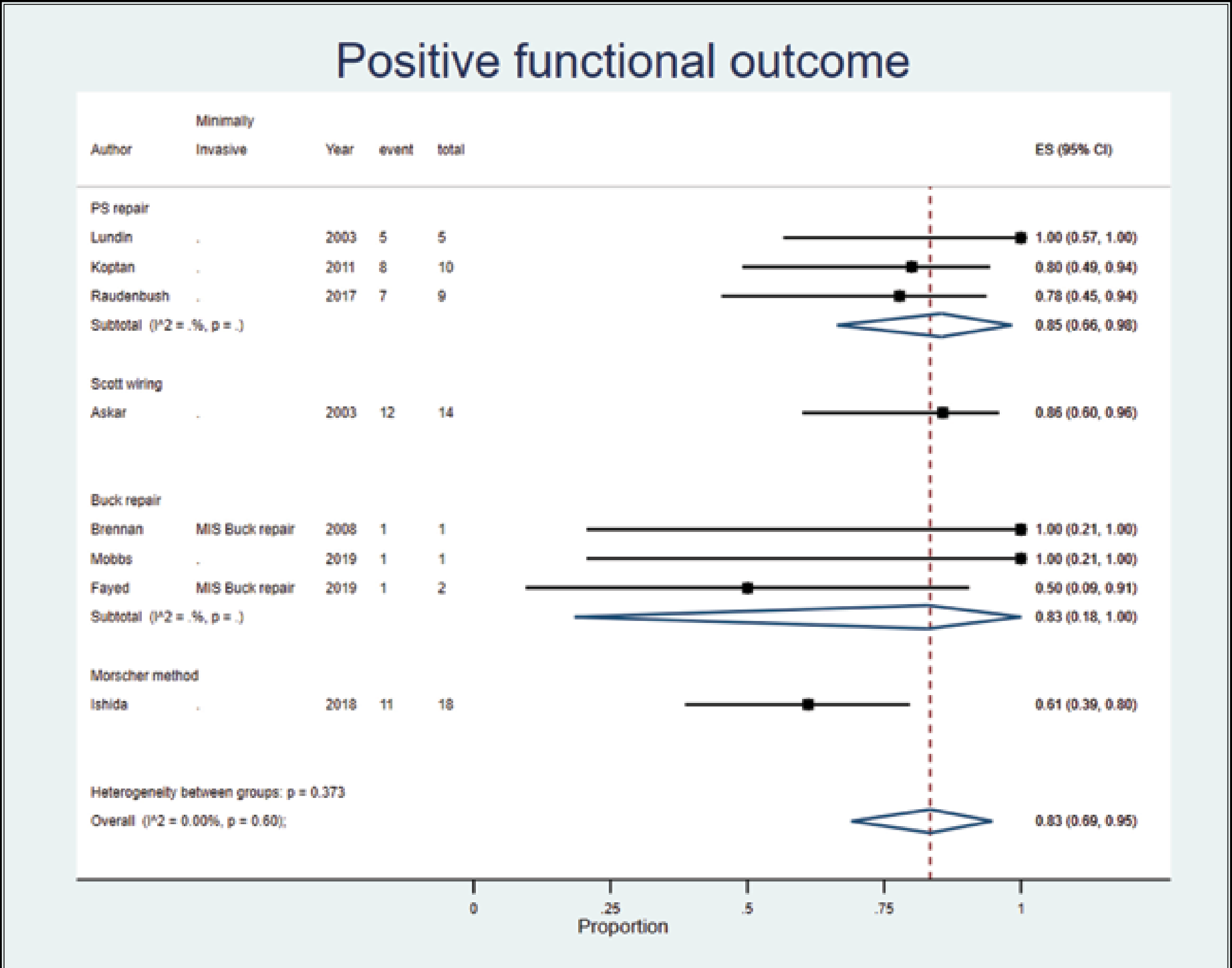
Supplemental Fig. 13. *Subgroup analysis of complication rates in female-predominant studies (more than half)*



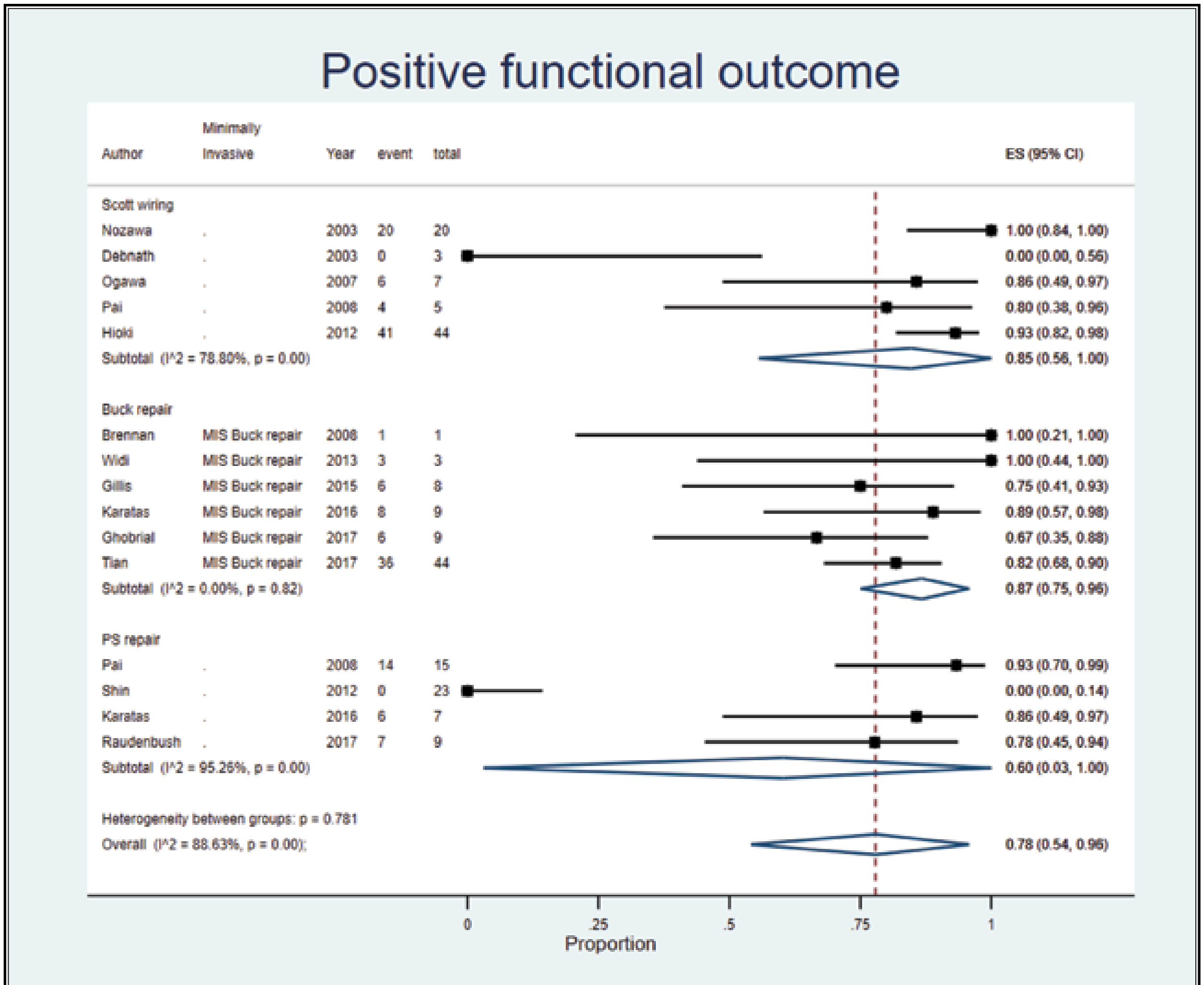
Supplemental Fig. 14. *Subgroup analysis of complication rates in sport population studies*



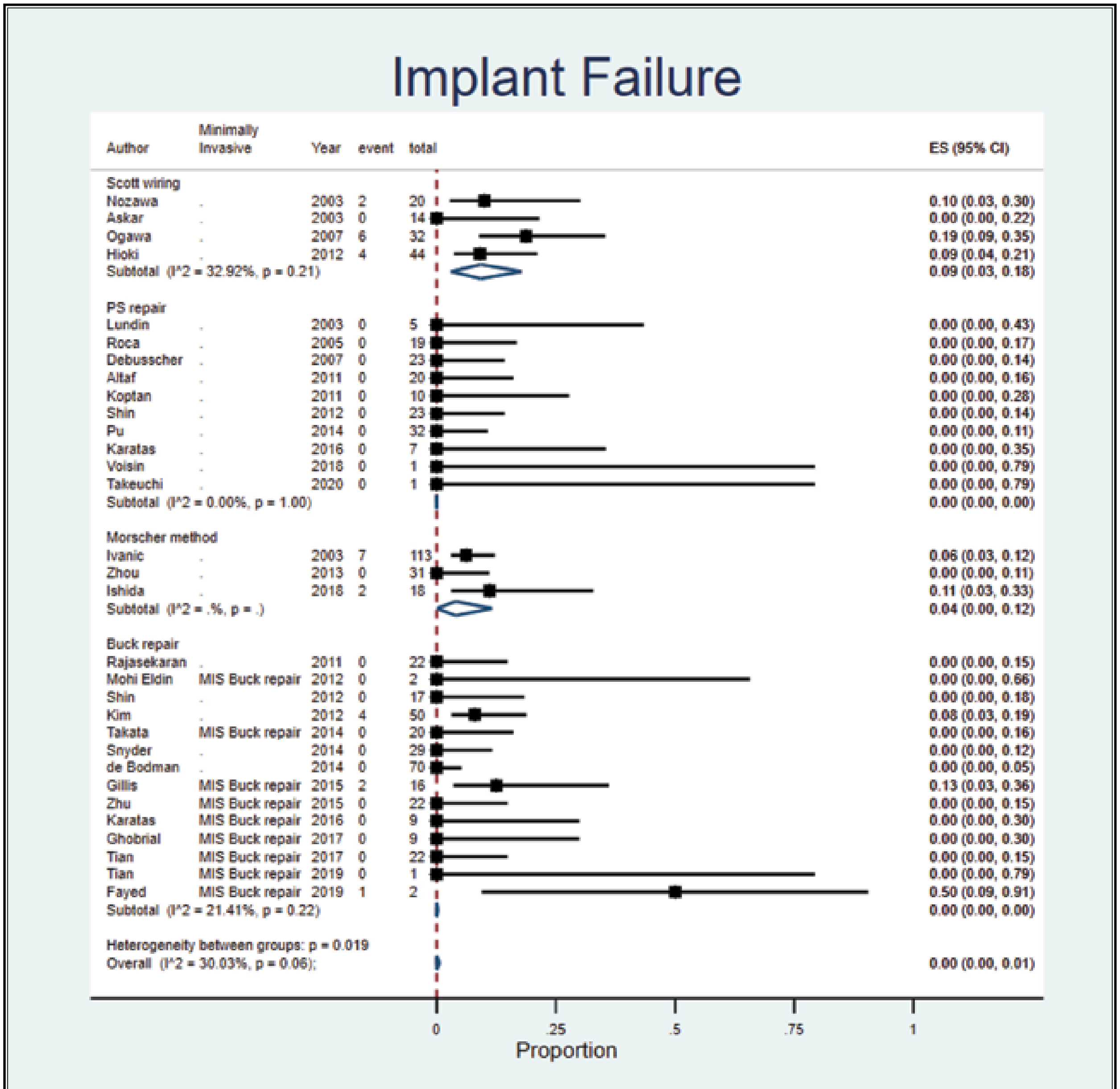
Supplemental Fig. 15. *Sensitivity analysis of positive functional outcome rates with studies followed up more than 1 year*



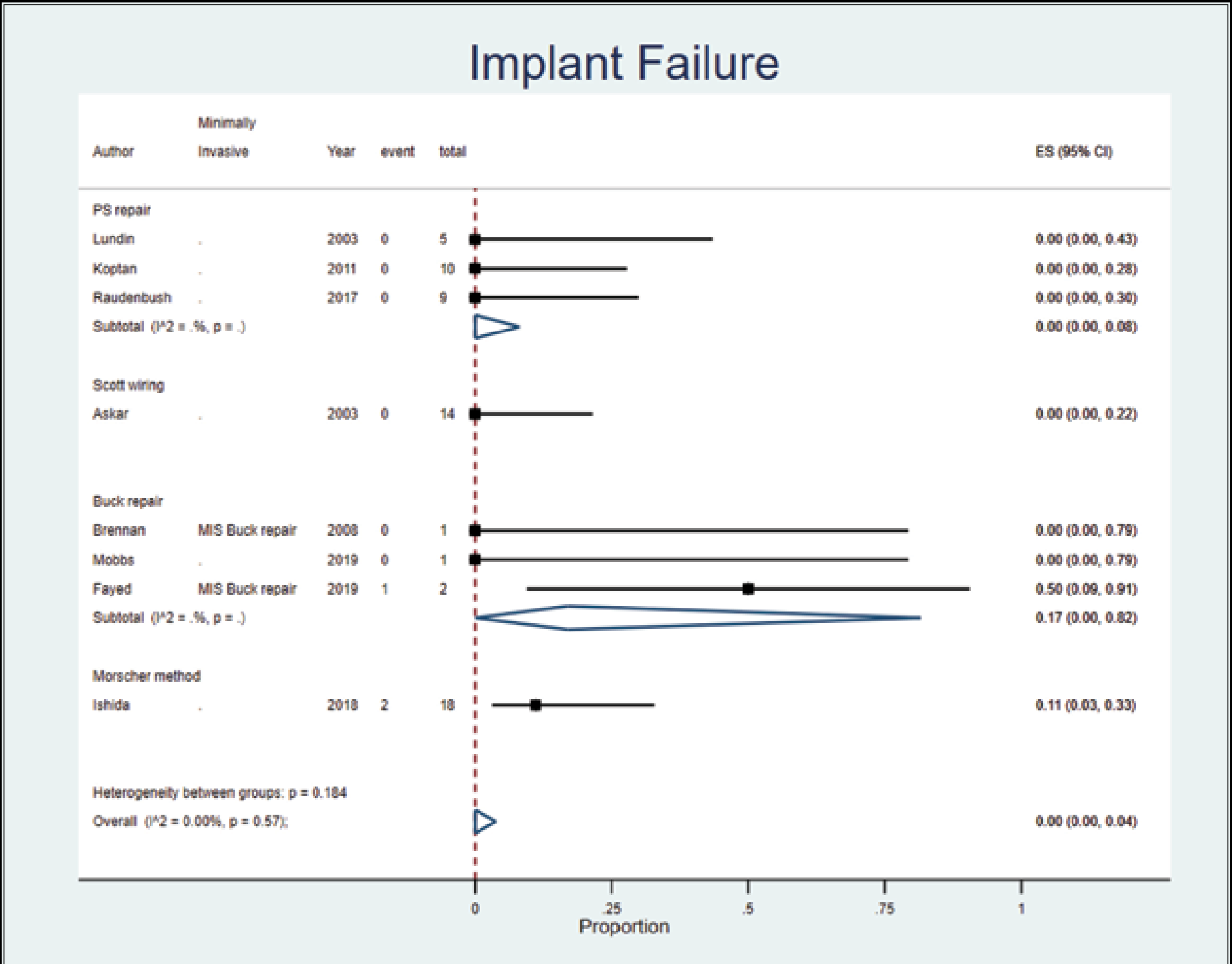
Supplemental Fig. 16. *Subgroup analysis of positive functional outcome in female-predominant studies (more than half)*



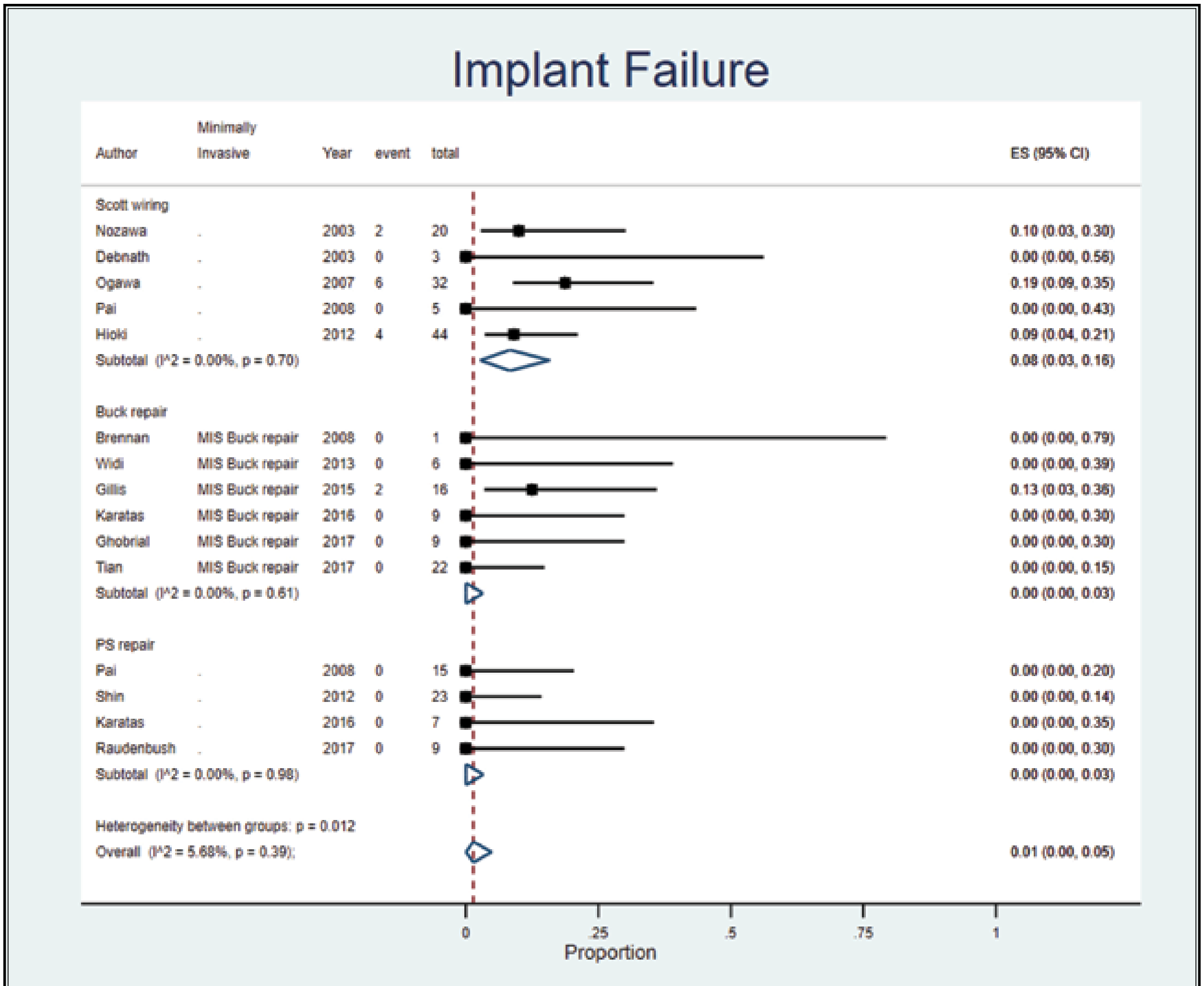
Supplemental Fig. 17. *Subgroup analysis of positive functional outcome in sport population studies*



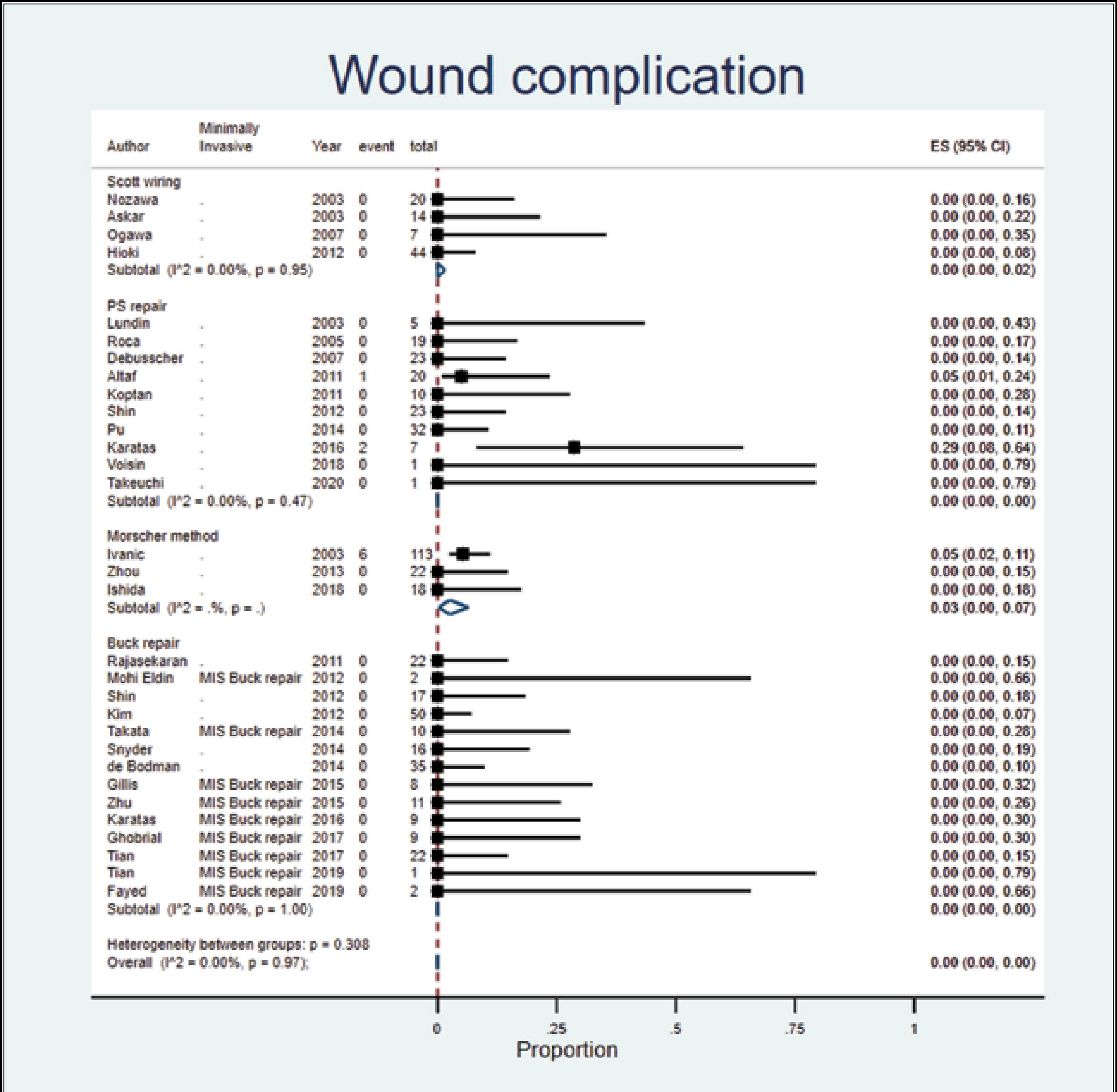
Supplemental Fig. 18. *Sensitivity analysis of implant failure rates with studies followed up more than 1 year*



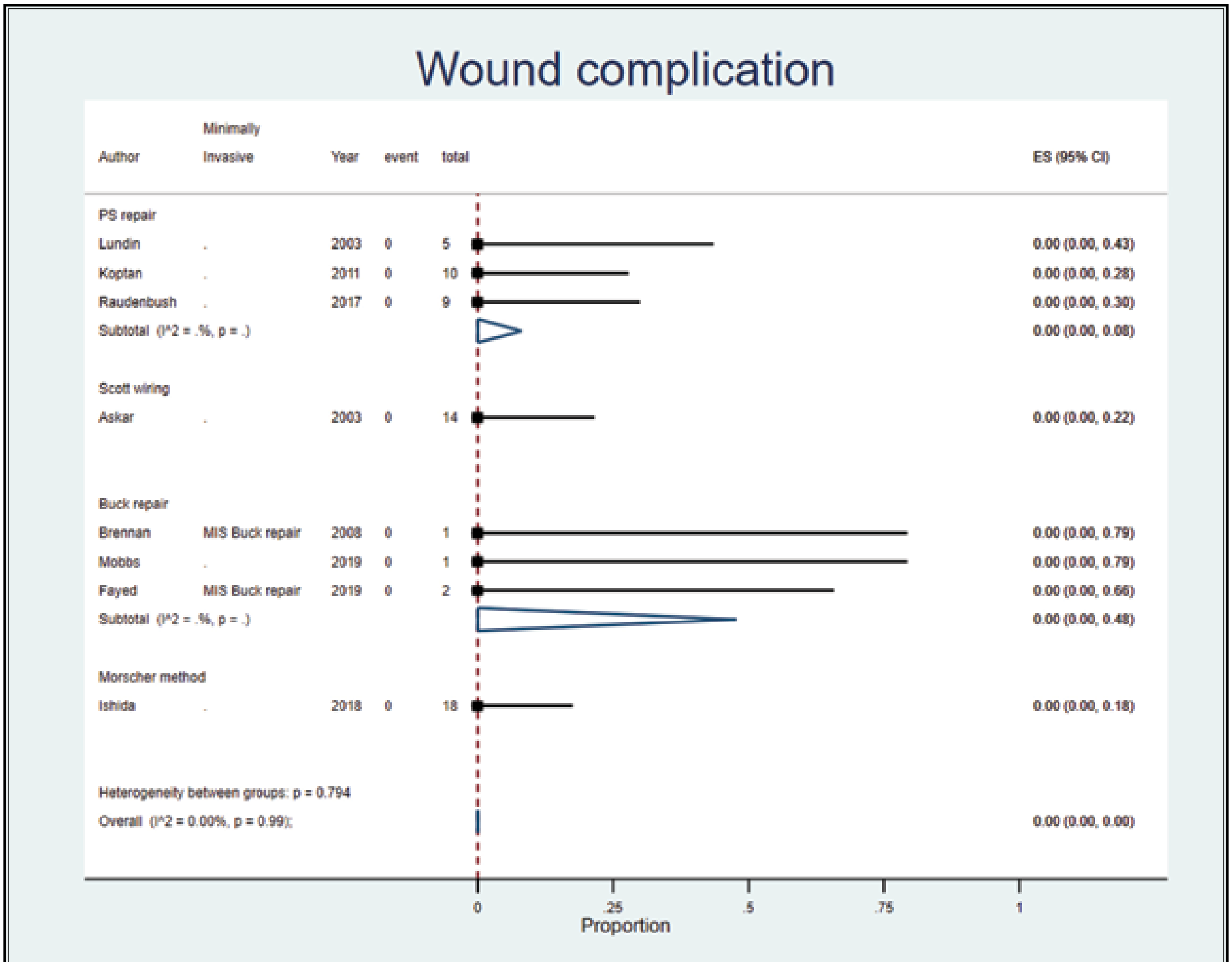
Supplemental Fig. 19. *Subgroup analysis of implant failure in female-predominant studies (more than half)*



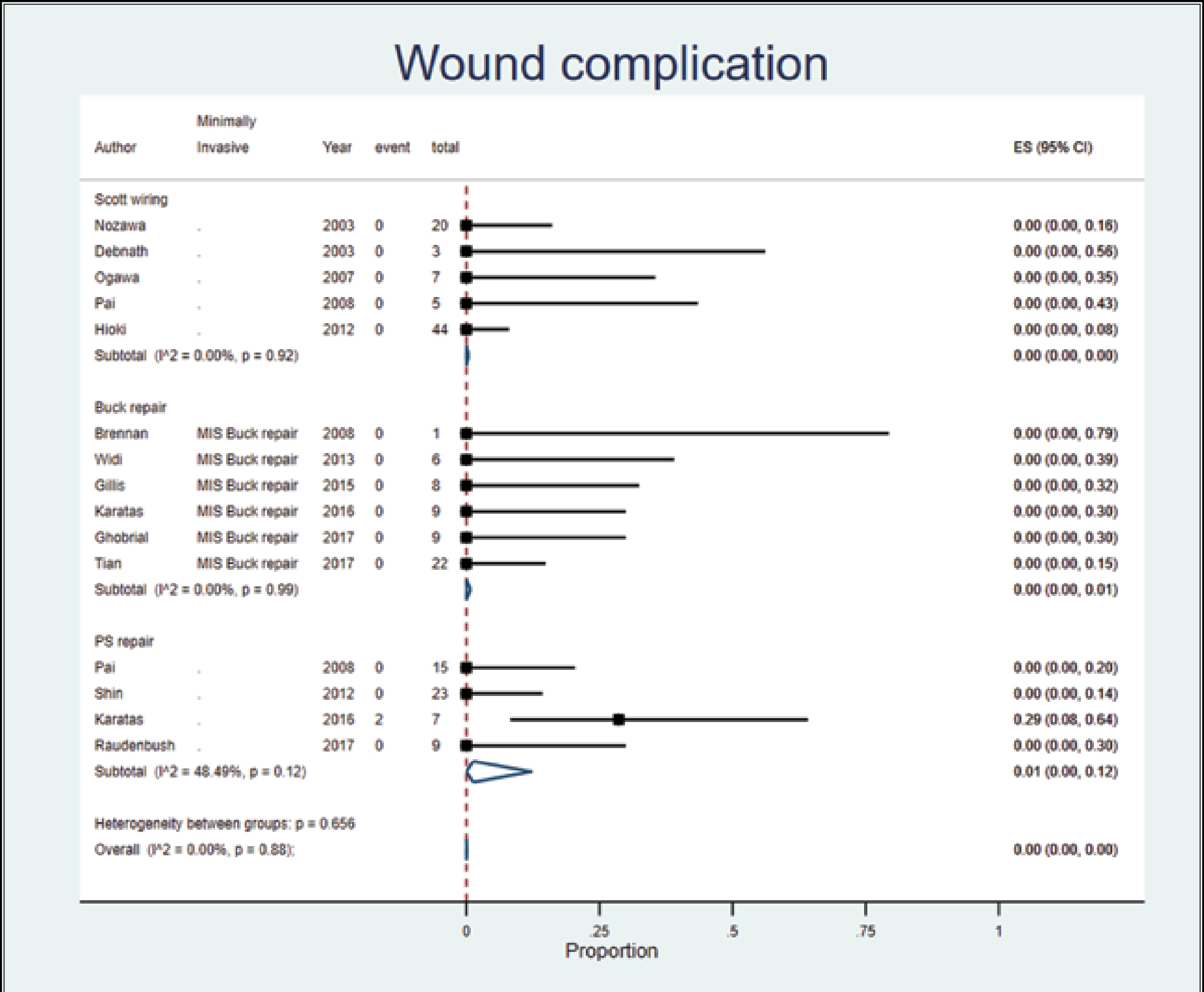
Supplemental Fig. 20. *Subgroup analysis of implant failure in sport population studies*



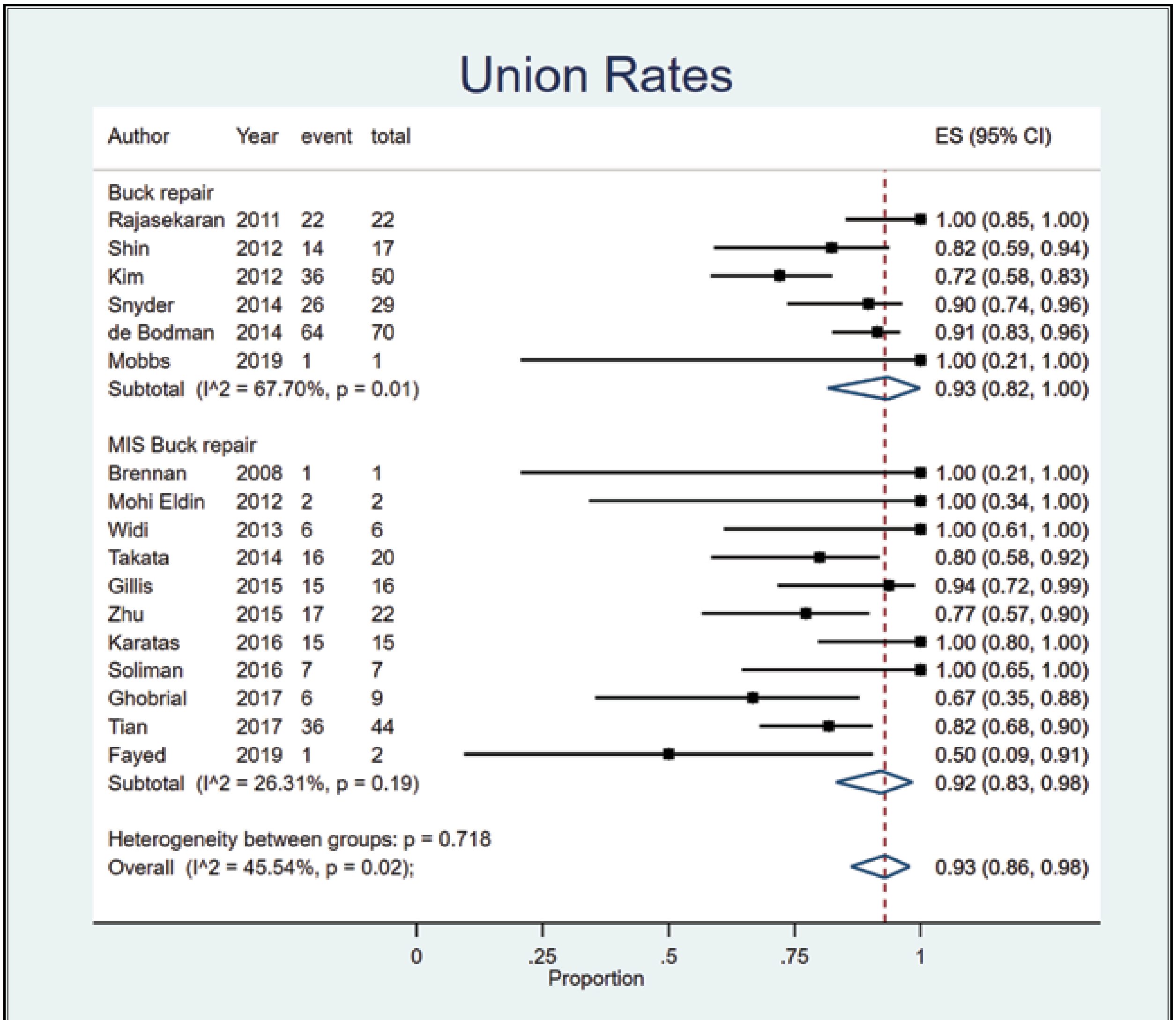
Supplemental Fig. 21. *Sensitivity analysis of wound complication rates with studies followed up more than 1 year*



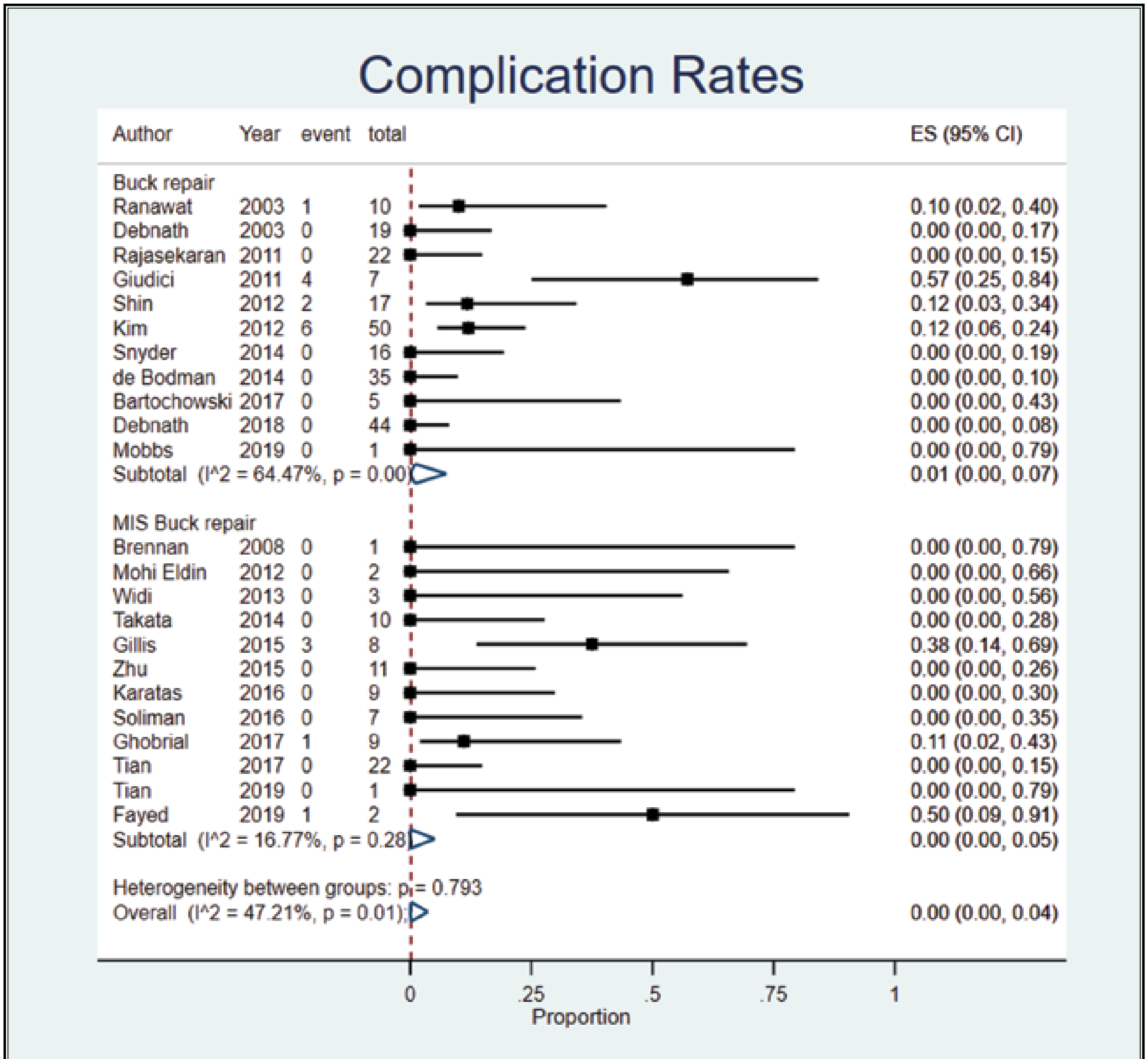
Supplemental Fig. 22. *Subgroup analysis of wound complications in female-predominant studies (more than half)*



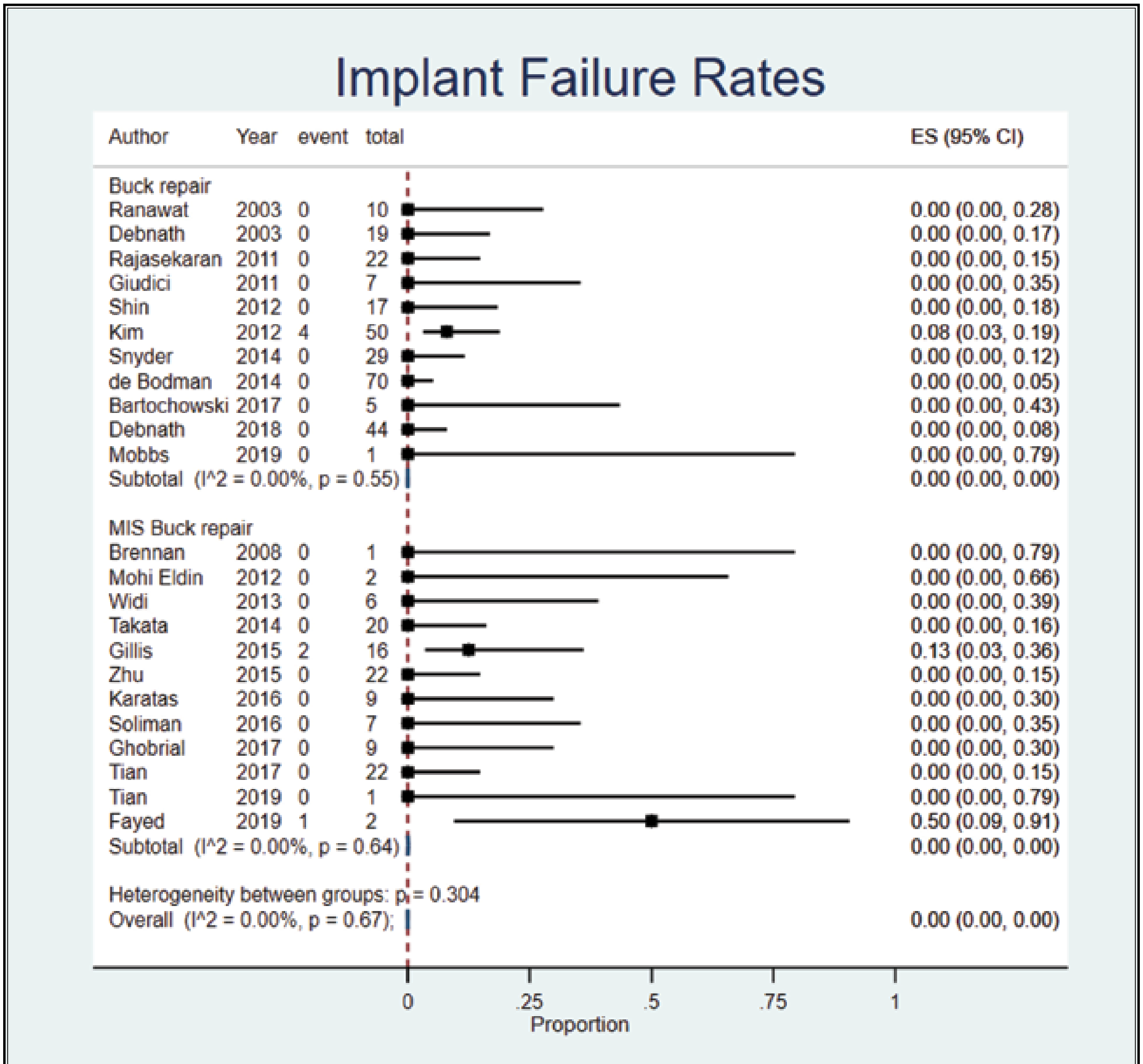
Supplemental Fig. 23. *Subgroup analysis of wound complications in sport population studies*



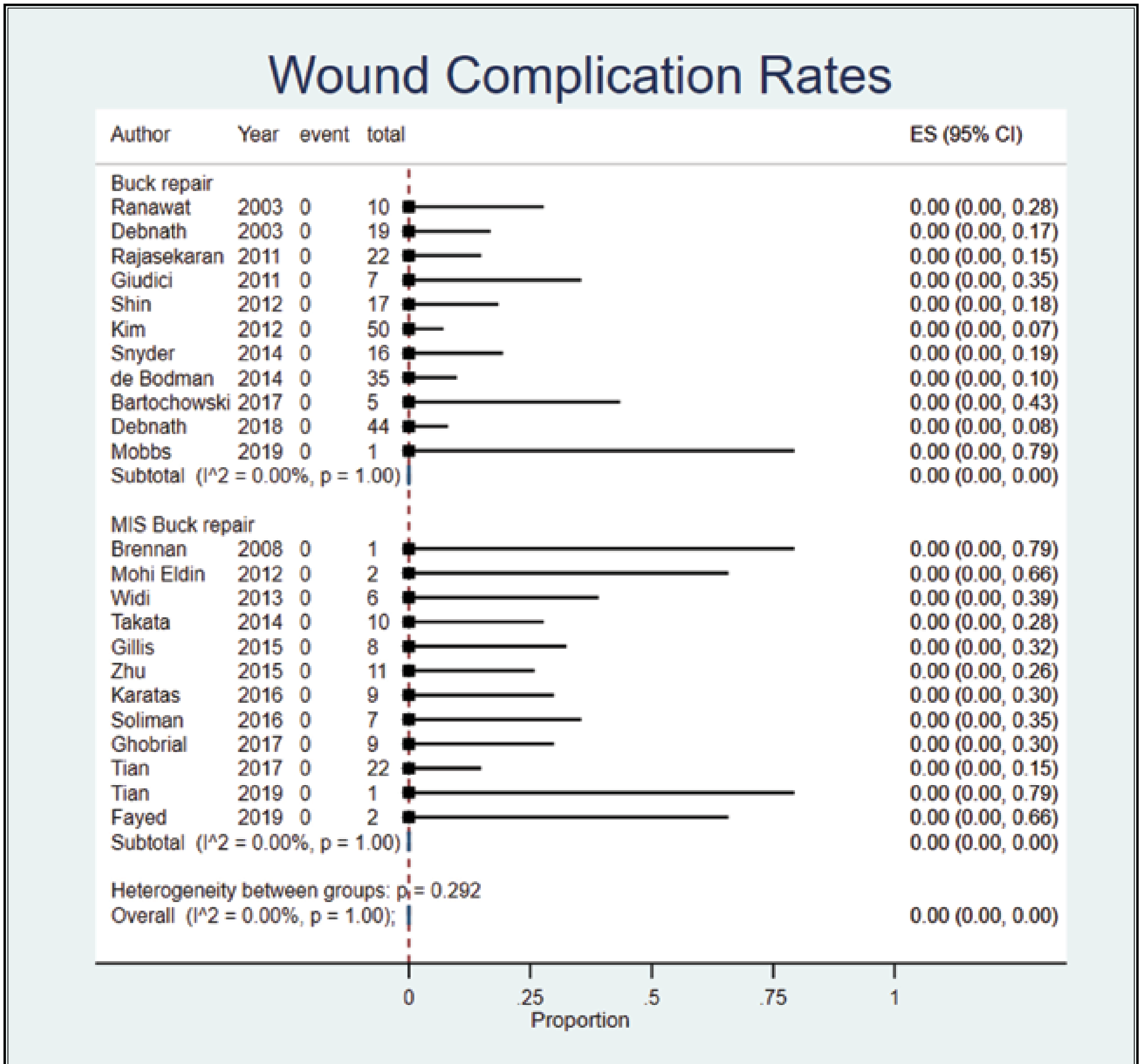
Supplemental Fig. 24. *Subgroup analysis of union rates in minimally invasive surgery versus open surgery studies*



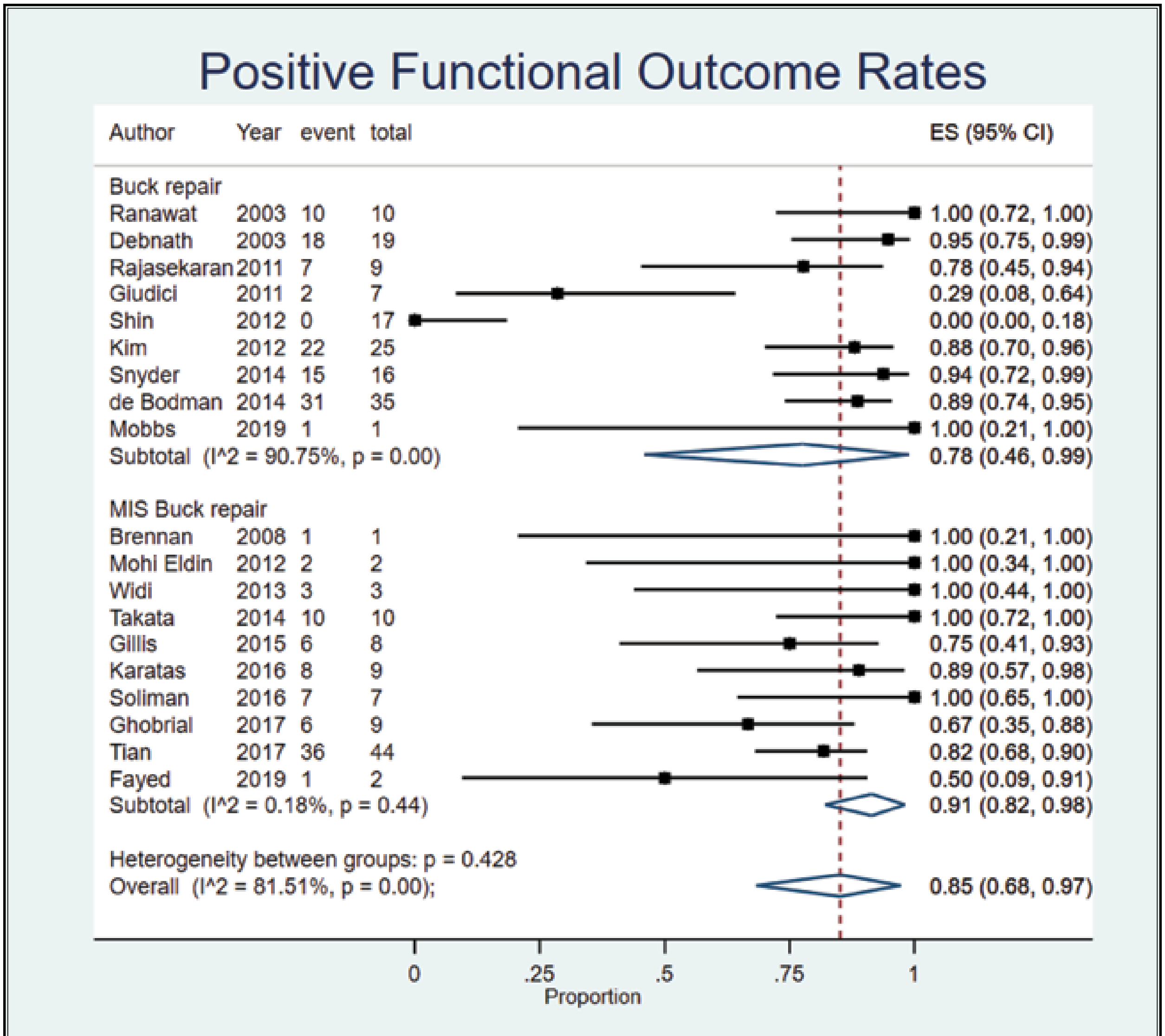
Supplemental Fig. 25. *Subgroup analysis of any complication rates in minimally invasive surgery versus open surgery studies*



Supplemental Fig. 26. *Subgroup analysis of implant failure complication rates in minimally invasive surgery versus open surgery studies*



Supplemental Fig. 27. *Subgroup analysis of wound compolication rates in minimally invasive surgery versus open surgery studies*



Supplemental Fig. 28. *Subgroup analysis of positive functional outcome rates in minimally invasive surgery versus open surgery studies*

Supplemental Table 1: *Risk of bias table*

Assessment of the Quality of Included Studies According to the Newcastle-Ottawa Quality Assessment Scale						
Study	**Quality Assessment Criteria**					
	Representativeness of Cohort	**Ascertainment of Exposure**	**Outcome of Interest**	**Assessment of Outcome**	**Adequate Duration**	**Adequate Follow-up of Cohort**
Sairyo, 2003	*	*	*	*		
Nozawa, 2003	*	*	*	*	*	*
Lundin, 2003	*	*	*	*	*	*
Ranawat, 2003	*	*	*	*		
Debnath, 2003	*	*	*	*		
Lutsey 2020	*	*	*	*		
Askar, 2003	*	*	*	*	*	*
Ivanic, 2003	*	*	*	*	*	*
Roca, 2005	*	*	*	*	*	*
Schlenzka, 2006	*	*	*	*		
Ogawa, 2007	*	*	*	*	*	*
Debusscher, 2007	*	*	*	*	*	*
Noggle, 2008	*	*	*	*		
Brennan, 2008	*	*	*	*		
Pai, 2008	*	*	*	*		
Rajasekaran, 2011	*	*	*	*	*	*
Giudici, 2011	*	*	*	*		
Altaf, 2011	*	*	*	*	*	*
Koptan, 2011	*	*	*	*	*	*
Mohi Eldin, 2012	*	*	*	*	*	*
Shin, 2012	*	*	*	*	*	*
Kim, 2012	*	*	*	*	*	*
Hioki, 2012	*	*	*	*	*	*
Widi, 2013	*	*	*	*		
Zhou, 2013	*	*	*	*	*	*
Takata, 2014	*	*	*	*	*	*
Snyder, 2014	*	*	*	*	*	*
Menga, 2014	*	*	*	*		
de Bodman, 2014	*	*	*	*	*	*
Pu, 2014	*	*	*	*	*	*
Gillis, 2015	*	*	*	*	*	*
Zhu, 2015	*	*	*	*	*	*
Karatas, 2016	*	*	*	*	*	*
Ghobrial, 2017	*	*	*	*	*	*
Bartochowski, 2017	*	*	*	*		
Raudenbush, 2017	*	*	*	*		
Tian, 2017	*	*	*	*	*	*
Voisin, 2018	*	*	*	*	*	*
Debnath, 2018	*	*	*	*		
Ishida, 2018	*	*	*	*	*	*

Supplemental Table 1 (cont.). *Risk of bias table*

Assessment of the Quality of Included Studies According to the Newcastle-Ottawa Quality Assessment Scale						
Study	**Quality Assessment Criteria**					
	Representativeness of Cohort	**Ascertainment of Exposure**	**Outcome of Interest**	**Assessment of Outcome**	**Adequate Duration**	**Adequate Follow-up of Cohort**
Tian, 2019	*	*	*	*	*	*
Mobbs, 2019	*	*	*	*		
Fayed, 2019	*	*	*	*	*	*
Takeuchi, 2020	*	*	*	*	*	*
Ucer , 2020	*	*	*	*	*	*

Supplemental Table 2. *Assessment of the Quality of Included Studies According to the GRADE Assessment Scale*

Outcome	**Quality Assessment Criteria**							
	Number of Studies	**Number of Patients**	**Inconsistency**	**Indirectness**	**Imprecision**	**Other consideration (Biases)**	**Relative Effect (95% CI)**	**Confidence to Effect Estimates (GRADE)**
Overall	44	810	Serious	Not serious	Not serious	Not serious	-	Moderate
Fusion assessment	39	978	Serious	Not serious	Not serious	Not serious	90% (90,98)	Moderate
Any complications	44	825	Serious	Not serious	Not serious	Not serious	2% (0,5)	Moderate
Implant Failure	44	914	Serious	Not serious	Not serious	Not serious	0% (0,0)	Moderate
Wound Complications	44	803	Serious	Not serious	Not serious	Not serious	0% (0,0)	Moderate
Positive Functional Outcome	44	787	Serious	Not serious	Not serious	Serious	83% (73,92)	Severe

Supplemental Table 3. *Search strategies developed by experienced librarian*

Search Strategies:	
#	**Searches**
1	(pars adj3 (defect* or fractur*)).ti,ab,kw. or (Spondylolisthesis/su or Spondylolysis/su or (spondylolysis or spondylolisthesis).ti.)
2	((direct or morcher* or buck* or scott*) adj3 (repair or surg* or fusion or screw* or fixat* or graft*)).ti,ab,kw.
3	(hook* or rod* or wire or wiring).ti,ab,kw. and ("pedicle screw*".ti,ab,kw. or *bone screws/ or *Bone Wires/ or Pedicle Screws/)
4	exp minimally invasive surgical procedures/
5	exp minimally invasive surgery/
6	exp *robotics/
7	exp *robotic surgical procedure/
8	(micro-surg* or microsurg* or mini-surg* or minisurg* or MIS or "microscopic surg* or mini-endo*" or micro-endoscop* or microendoscop* or "minimally invasive" or "da Vinci" or davinci).ti,ab,hw,kw.
9	(((mini* or lap* or robot* or endoscop*) adj2 (technique* or approach or access or assist* or surg* or repair* or fusion or screw* or fixat* or graft*)) or (vertebroplasty or "mini-open")).ti,ab,kw.
10	or/2-9
11	1 and 10
12	11 not ((exp animals/ or exp nonhuman/) not exp humans/)
13	(conference abstract or conference review or editorial or erratum or note or addresses or autobiography or bibliography or biography or blogs or comment or dictionary or directory or interactive tutorial or interview or lectures or legal cases or legislation or news or newspaper article or patient education handout or periodical index or portraits or published erratum or video-audio media or webcasts).mp. [mp=ti, ab, ot, nm, hw, fx, kf, ox, px, rx, ui, sy, sh, kw, tx, ct, tn, dm, mf, dv, dq]
14	12 not 13
15	limit 14 to english language [Limit not valid in CDSR; records were retained]
16	limit 14 to no language specified [Limit not valid in CDSR; records were retained]
17	15 or 16
18	remove duplicates from 17

Database(s): Ovid MEDLINE(R) 1946 to Present and Epub Ahead of Print, In-Process & Other Non-Indexed Citations and Ovid MEDLINE(R) Daily, EBM Reviews - Cochrane Central Register of Controlled Trials June 2020, EBM Reviews - Cochrane Database of Systematic Reviews 2005 to July 31, 2020, Embase 1974 to 2020 August 06 and Scopus

1	TITLE-ABS-KEY ((pars w/2 (defect* or fractur*)) or spondylolysis or spondylolisthesis)
2	((direct or morcher* or buck* or scott*) w/2 (repair or surg* or fusion or screw* or fixat* or graft*))
3	TITLE-ABS-KEY ((hook* or rod* or wire or wiring) and "pedicle screw*")
4	TITLE (micro-surg* or microsurg* or mini-surg* or minisurg* or MIS or "microscopic surg* or mini-endo*" or micro-endoscop* or microendoscop* or "minimally invasive" or "da Vinci" or davinci)
5	TITLE (((mini* or lap* or robot* or endoscop*) w/2 (technique* or approach or access or assist* or surg* or repair* or fusion or screw* or fixat* or graft*)) or (vertebroplasty or "mini-open"))
6	2 or 3 or 4 or 5
7	1 and 6
8	INDEX(embase) OR INDEX(medline) OR PMID(0* OR 1* OR 2* OR 3* OR 4* OR 5* OR 6* OR 7* OR 8* OR 9*)
9	7 not 8
10	DOCTYPE(ed) OR DOCTYPE(bk) OR DOCTYPE(er) OR DOCTYPE(no) OR DOCTYPE(sh) OR DOCTYPE(ch)
11	9 not 10
12	LANGUAGE(english)
13	11 and 12

14	(TITLE-ABS-KEY ((alpaca OR alpacas OR amphibian OR amphibians OR animal OR animals OR antelope OR armadillo OR armadillos OR avian OR baboon OR baboons OR beagle OR beagles OR bee OR bees OR bird OR birds OR bison OR bovine OR buffalo OR buffaloes OR buffalos OR "c elegans" OR "Caenorhabditis elegans" OR camel OR camels OR canine OR canines OR carp OR cats OR cattle OR chick OR chicken OR chickens OR chicks OR chimp OR chimpanze OR chimpanzees OR chimps OR cow OR cows OR "D melanogaster" OR "dairy calf" OR "dairy calves" OR deer OR dog OR dogs OR donkey OR donkeys OR drosophila OR "Drosophila melanogaster" OR duck OR duckling OR ducklings OR ducks OR equid OR equids OR equine OR equines OR feline OR felines OR ferret OR ferrets OR finch OR finches OR fish OR flatworm OR flatworms OR fox OR foxes OR frog OR frogs OR "fruit flies" OR "fruit fly" OR "G mellonella" OR "Galleria mellonella" OR geese OR gerbil OR gerbils OR goat OR goats OR goose OR gorilla OR gorillas OR hamster OR hamsters OR hare OR hares OR heifer OR heifers OR horse OR horses OR insect OR insects OR jellyfish OR kangaroo OR kangaroos OR kitten OR kittens OR lagomorph OR lagomorphs OR lamb OR lambs OR llama OR llamas OR macaque OR macaques OR macaw OR macaws OR marmoset OR marmosets OR mice OR minipig OR minipigs OR mink OR minks OR monkey OR monkeys OR mouse OR mule OR mules OR nematode OR nematodes OR octopus OR octopuses OR orangutan OR "orang-utan" OR orangutans OR "orang-utans" OR oxen OR parrot OR parrots OR pig OR pigeon OR pigeons OR piglet OR piglets OR pigs OR porcine OR primate OR primates OR quail OR rabbit OR rabbits OR rat OR rats OR reptile OR reptiles OR rodent OR rodents OR ruminant OR ruminants OR salmon OR sheep OR shrimp OR slug OR slugs OR swine OR tamarin OR tamarins OR toad OR toads OR trout OR urchin OR urchins OR vole OR voles OR waxworm OR waxworms OR worm OR worms OR xenopus OR "zebra fish" OR zebrafish) AND NOT (human OR humans OR patient OR patients)))
15	13 not 14