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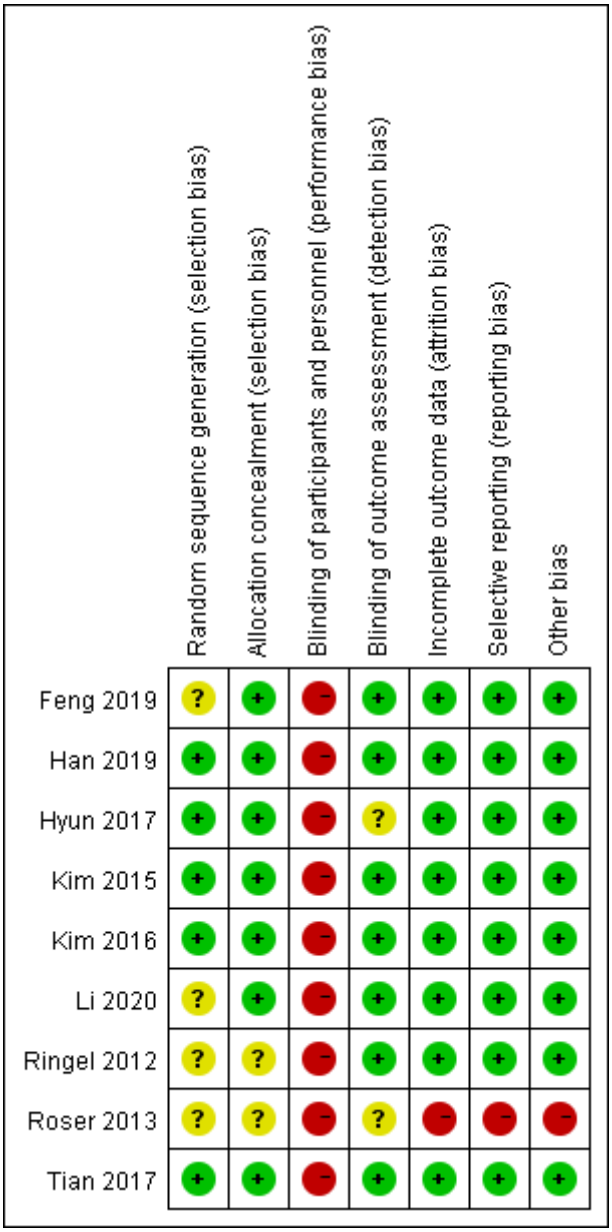
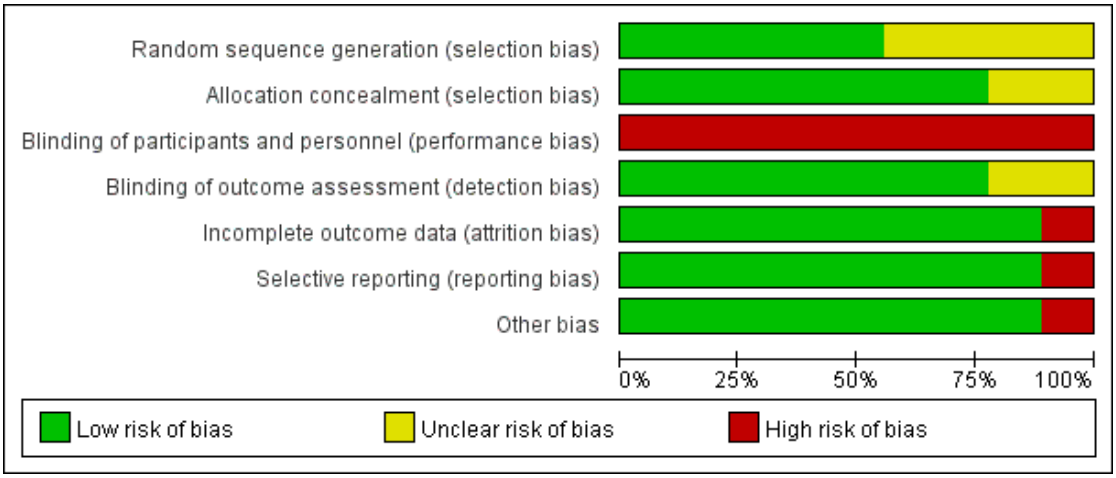
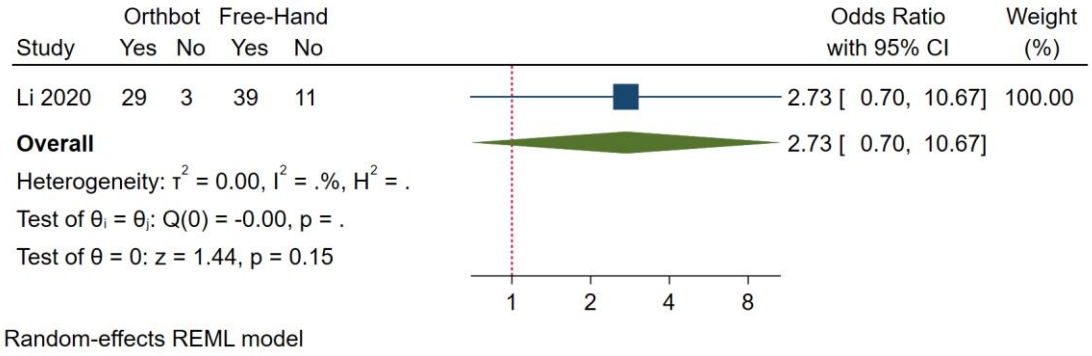
Supplementary Figure 1. Risk of bias summary of included studies.



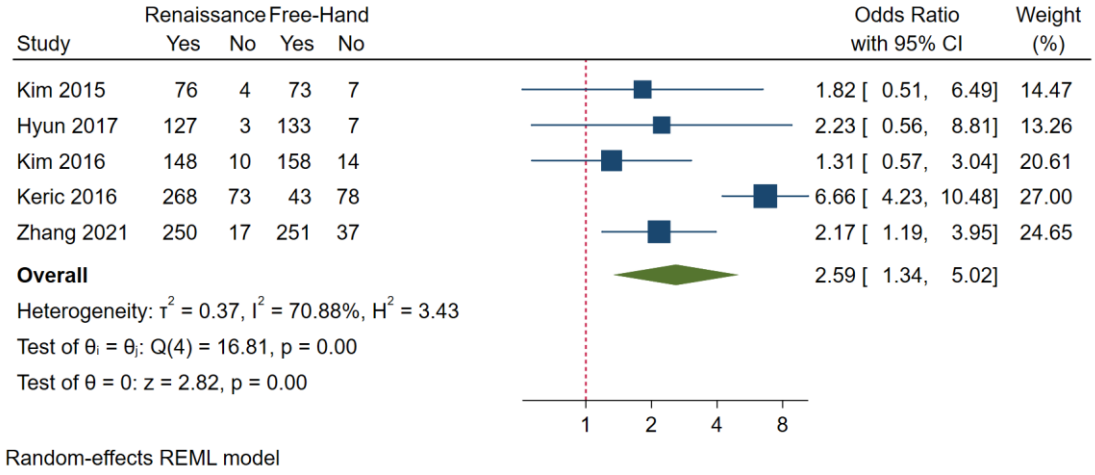
Supplementary Figure 2. Risk of bias of included studies.



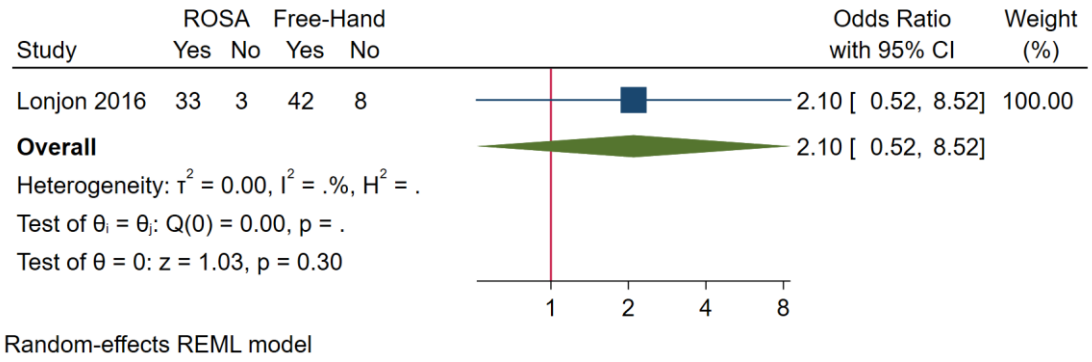
Supplementary Figure 3. Orthbot compared with Free-Hand on perfect pedicle screw insertion.



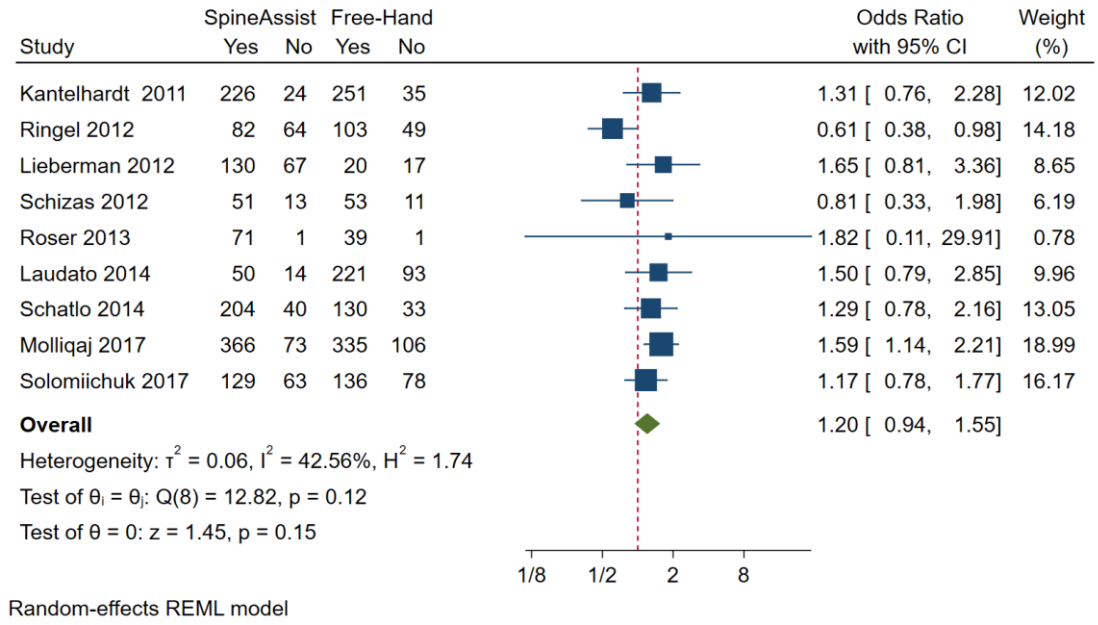
Supplementary Figure 4. Renaissance compared with Free-Hand on perfect pedicle screw insertion.



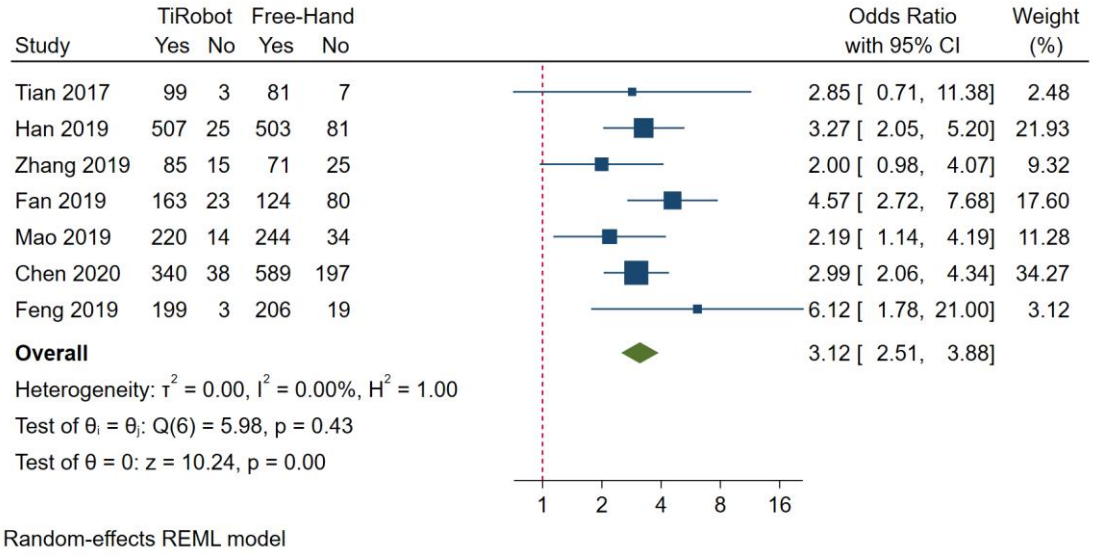
Supplementary Figure 5. ROSA compared with Free-Hand on perfect pedicle screw insertion.



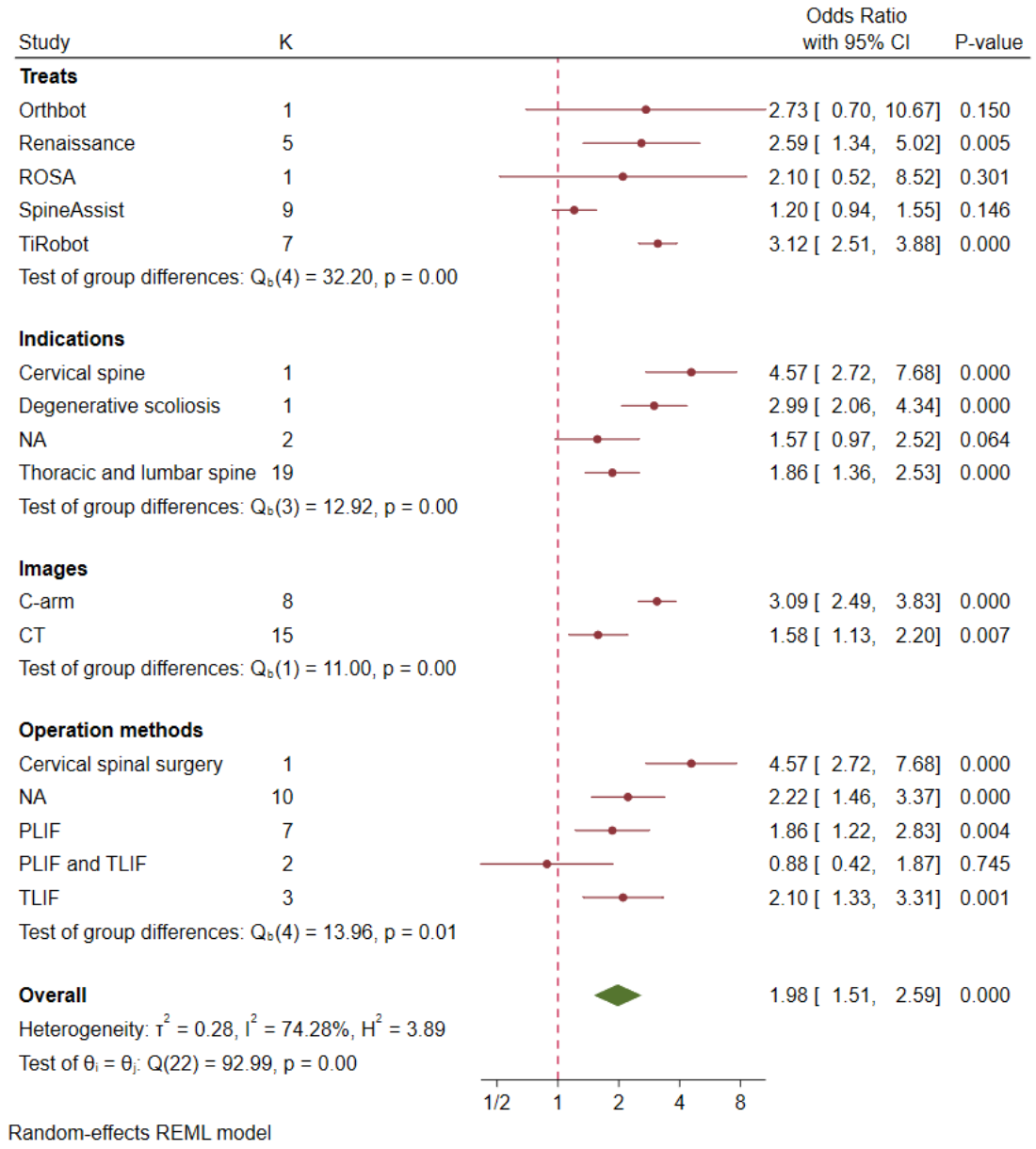
Supplementary Figure 6. SpineAssist compared with Free-Hand on perfect pedicle screw insertion.



Supplementary Figure 7. TiRobot compared with Free-Hand on perfect pedicle screw insertion.

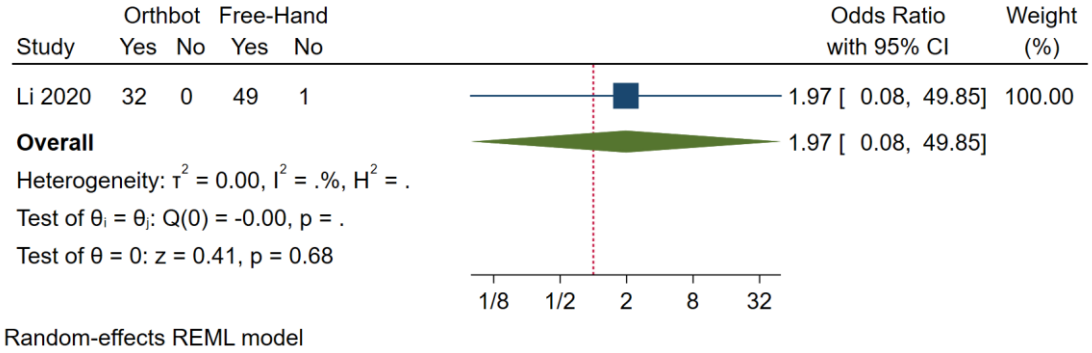


Supplementary Figure 8. Subgroup analysis of perfect pedicle screw insertion.

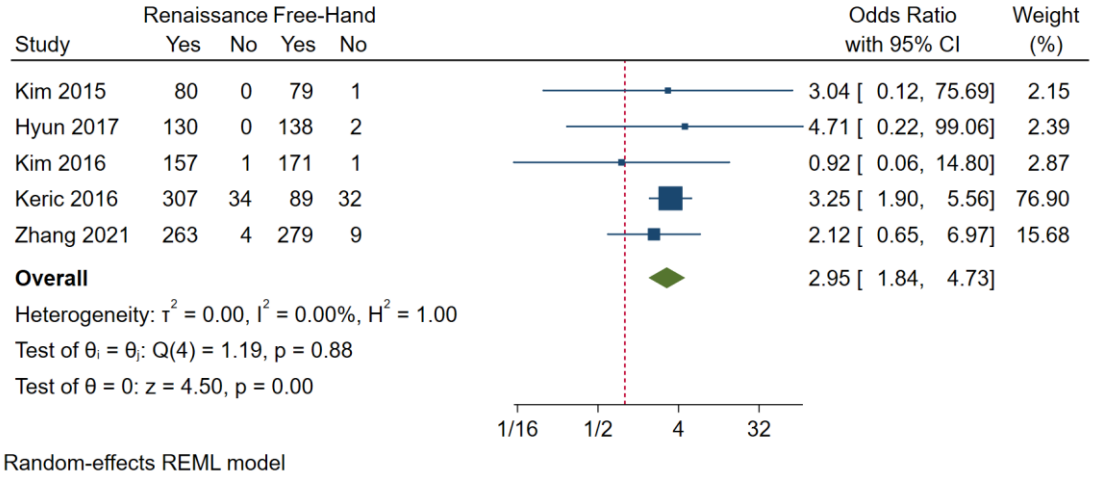


CT: computed tomography; PLIF: Posterior lumbar interbody fusion; TLIF: Transforaminal lumbar interbody fusion.

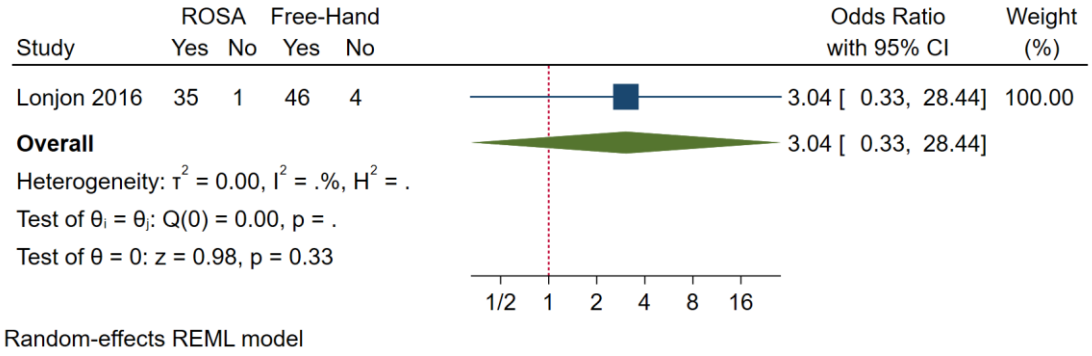
Supplementary Figure 9. Orthbot compared with Free-Hand on clinically acceptable pedicle.



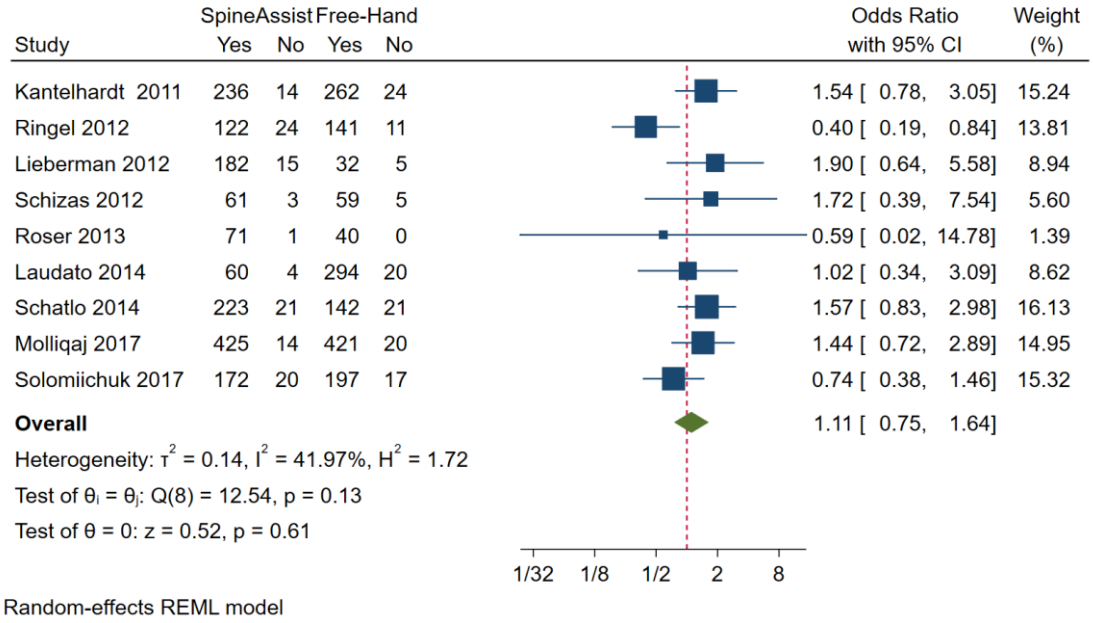
Supplementary Figure 10. Renaissance compared with Free-Hand on clinically acceptable pedicle.



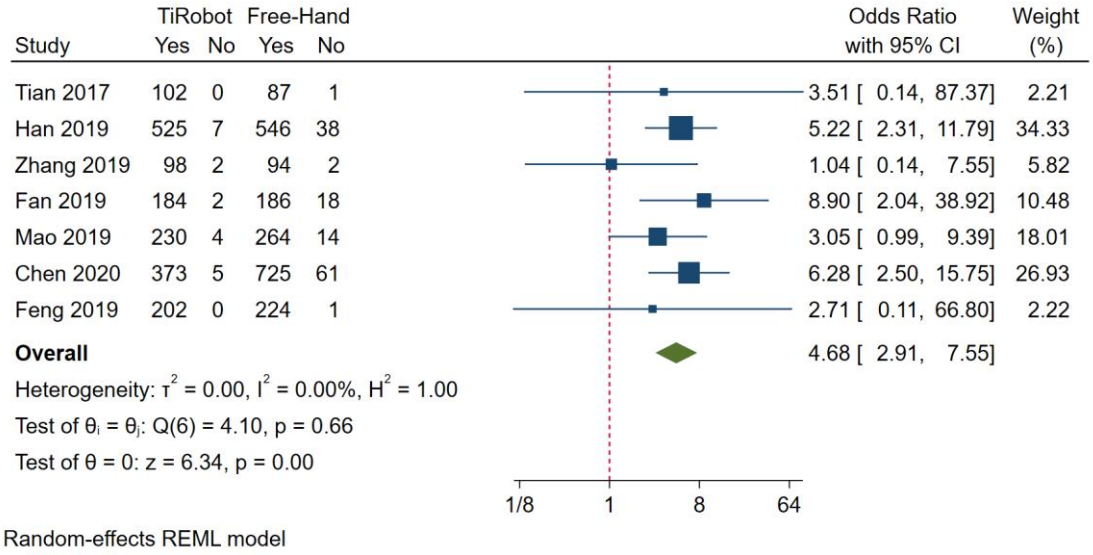
Supplementary Figure 11. ROSA compared with Free-Hand on clinically acceptable pedicle.



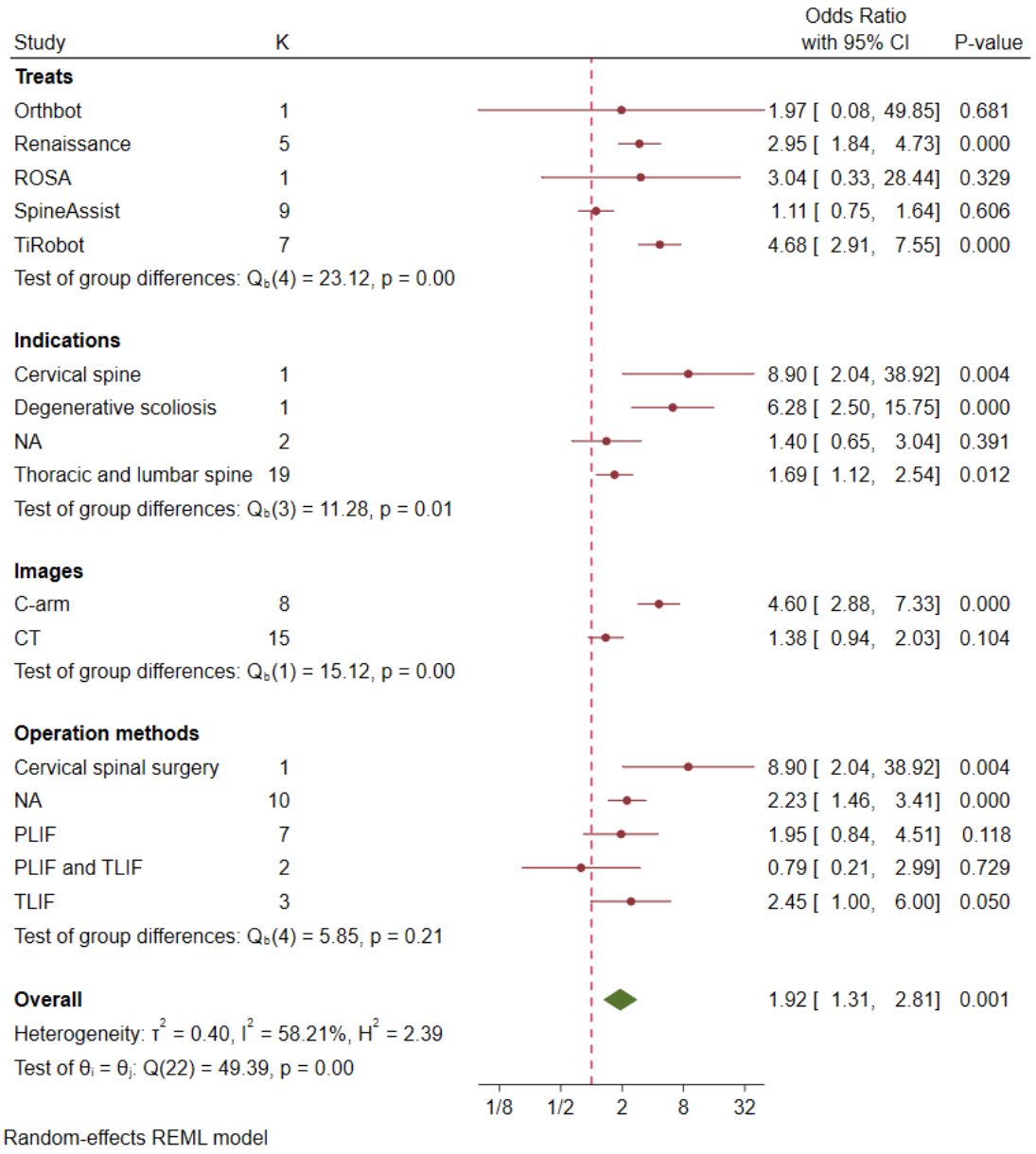
Supplementary Figure 12. SpineAssist compared with Free-Hand on clinically acceptable pedicle.



Supplementary Figure 13. TiRobot compared with Free-Hand on clinically acceptable pedicle.



Supplementary Figure 14. Subgroup analysis of clinically acceptable pedicle.



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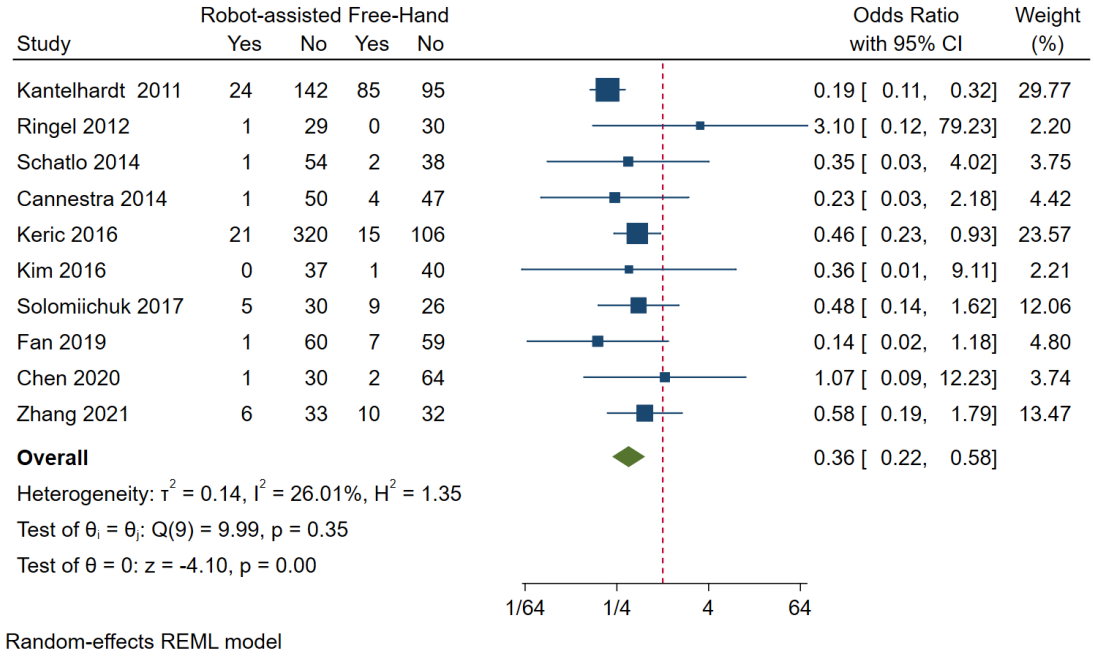
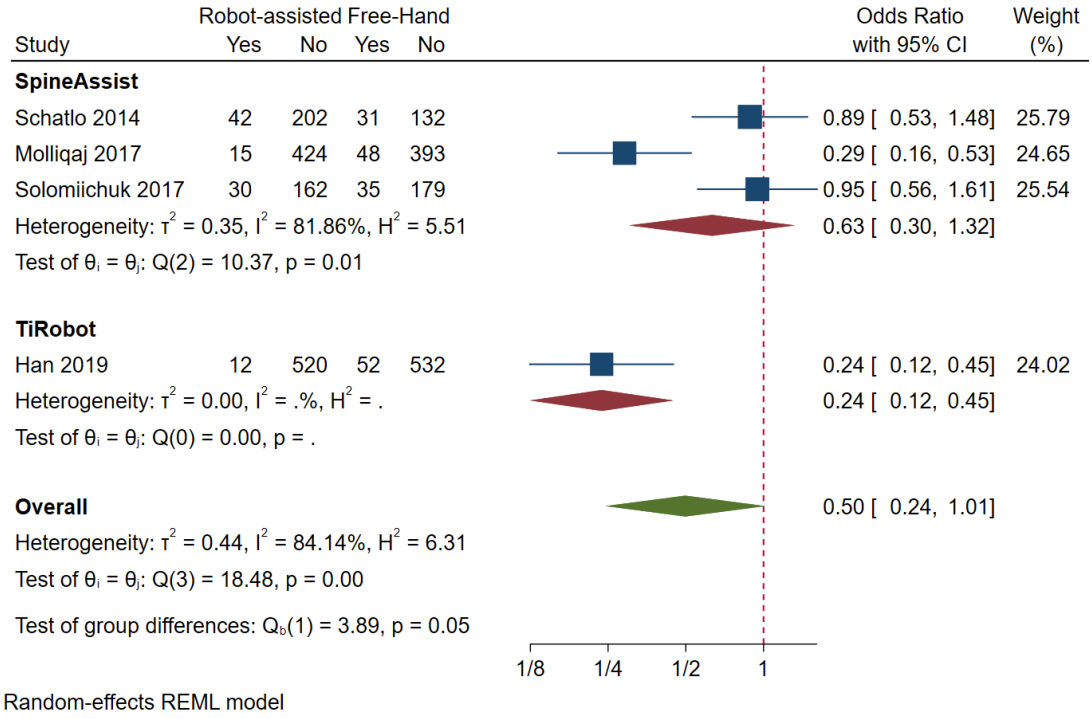
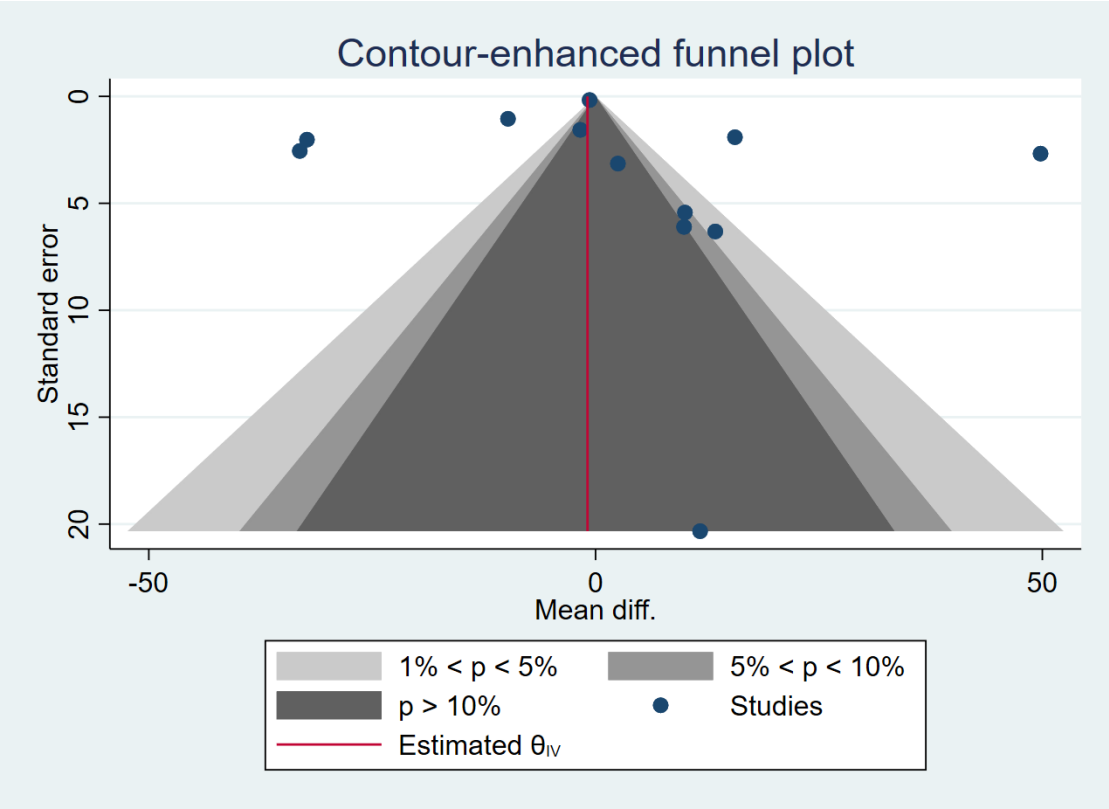
Supplementary Figure 15. Sensitivity analysis of overall complications during comparison between the robot-assisted technique versus the conventional freehand technique (excluding Zahrawi 2014).



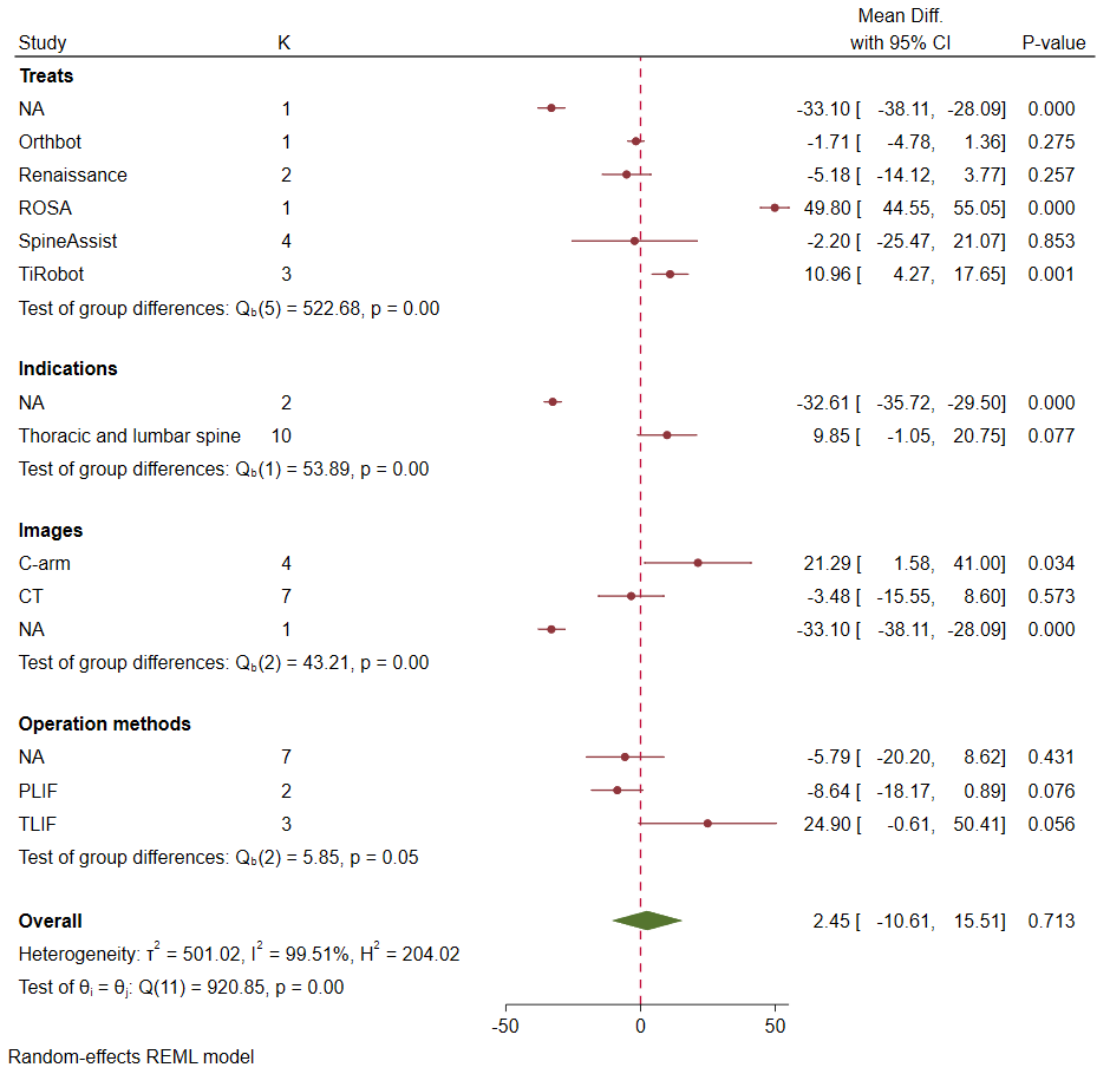
Supplementary Figure 16. Subgroup analysis of screw misplacement rate.



Supplementary Figure 17. Contour-enhanced funnel plot of radiation exposure time.

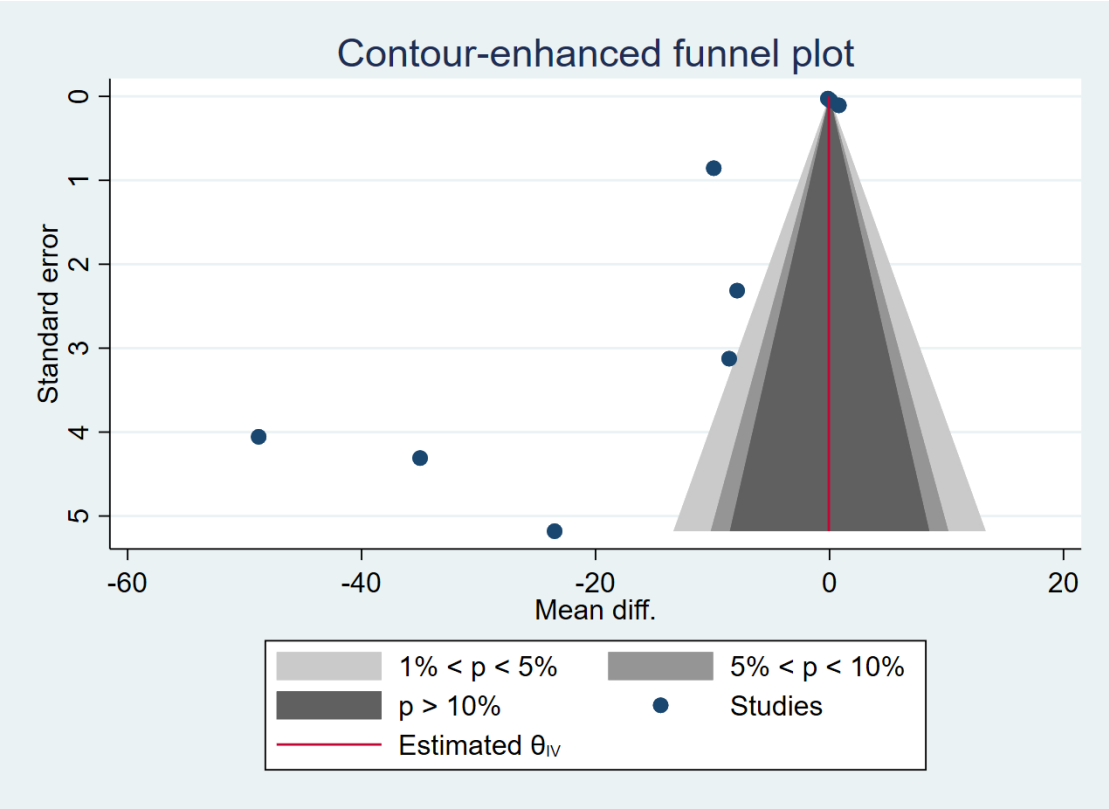


Supplementary Figure 18. Subgroup analysis of radiation exposure time.

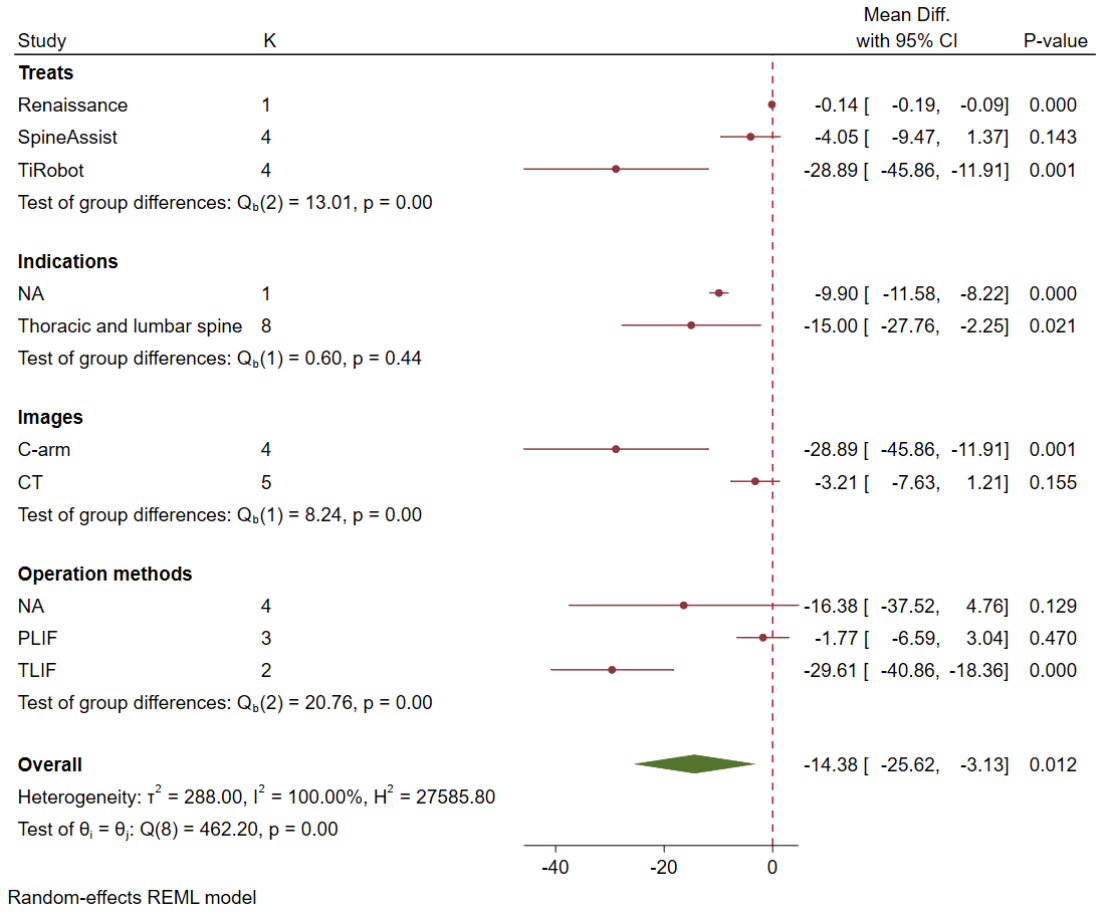


CT: computed tomography; PLIF: Posterior lumbar interbody fusion; TLIF: Transforaminal lumbar interbody fusion.

Supplementary Figure 19. Contour-enhanced funnel plot of radiation dosage.

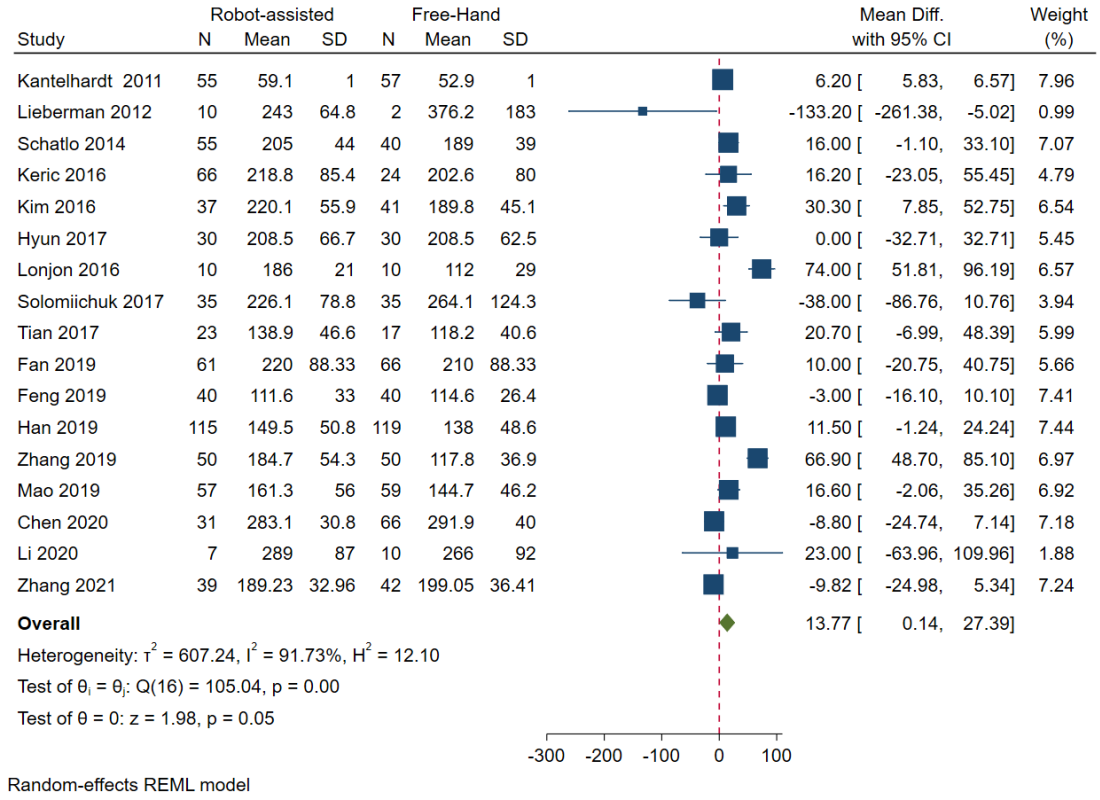


Supplementary Figure 20. Subgroup analysis of radiation dosage.

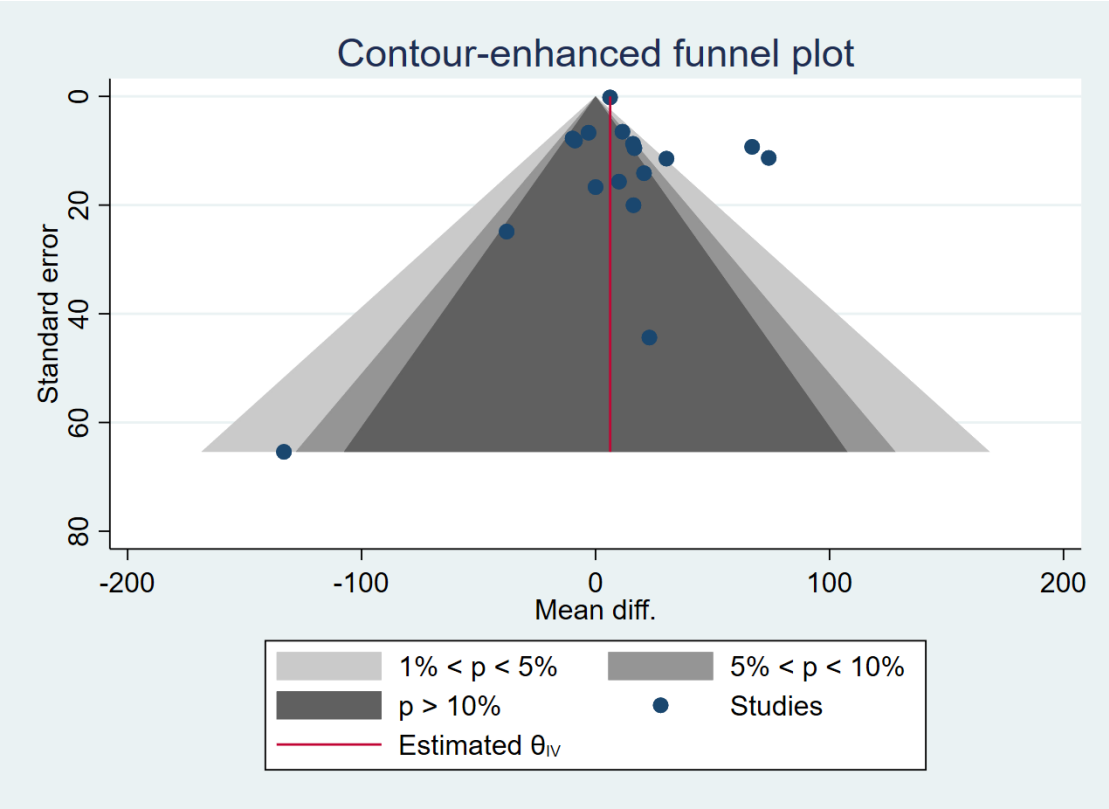


CT: computed tomography; PLIF: Posterior lumbar interbody fusion; TLIF: Transforaminal lumbar interbody fusion.

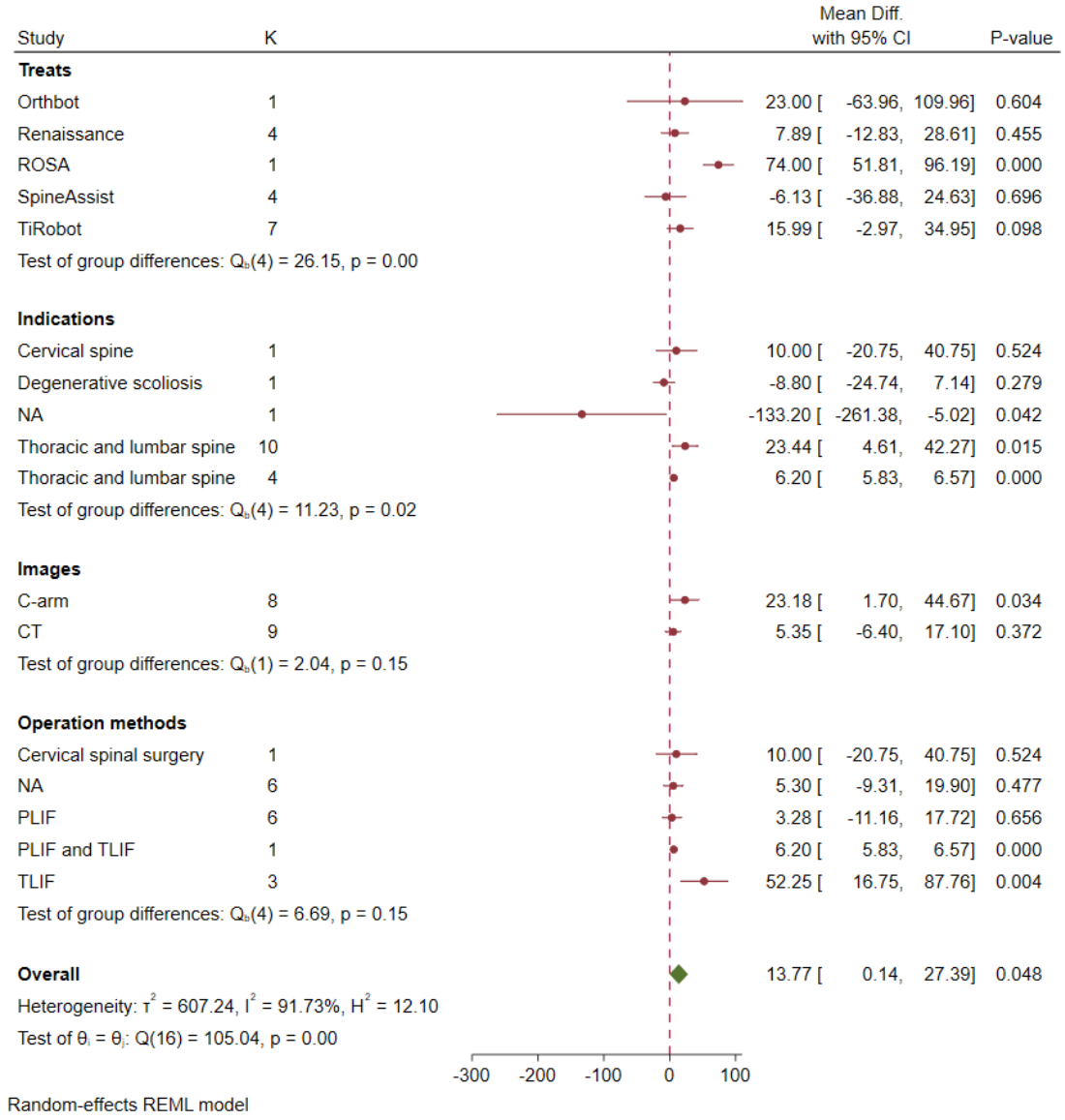
Supplementary Figure 21. Pooled analysis of operative time.



Supplementary Figure 22. Contour-enhanced funnel plot of operative time.

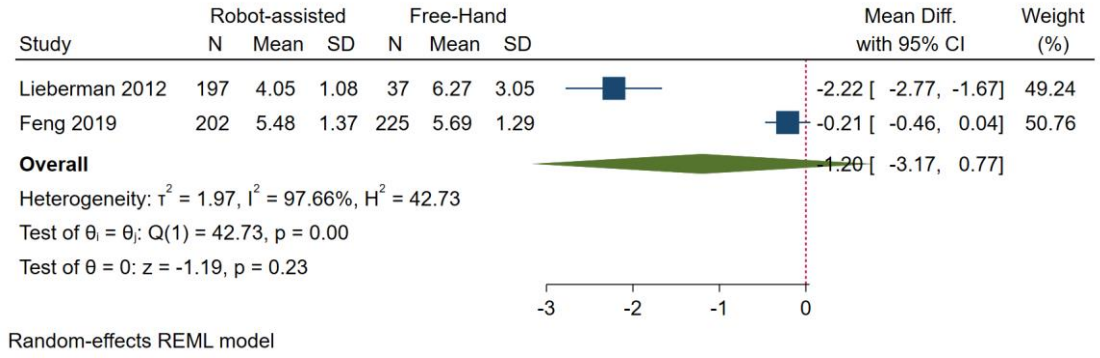


Supplementary Figure 23. Subgroup analysis of operative time.

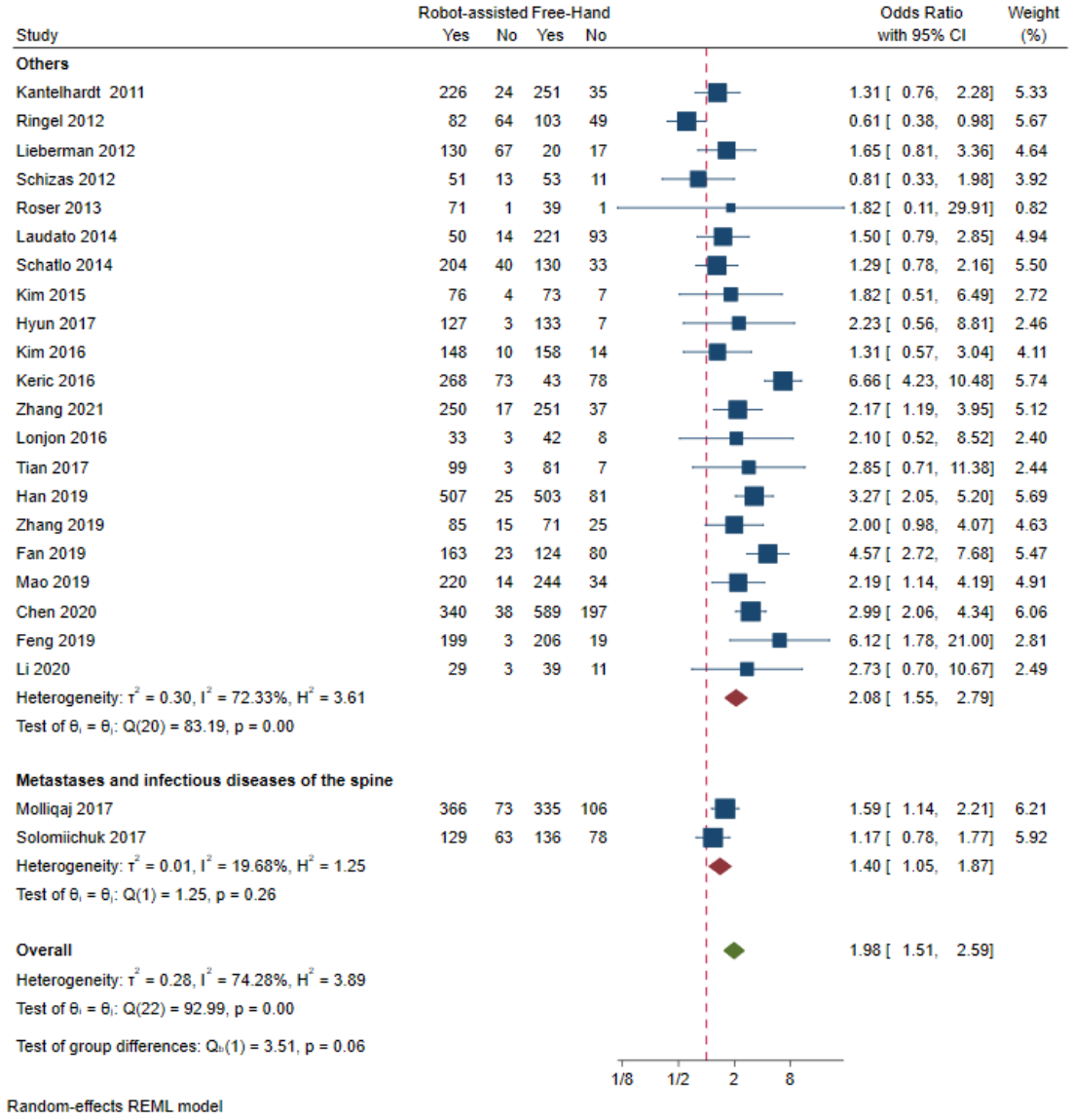


CT: computed tomography; PLIF: Posterior lumbar interbody fusion; TLIF: Transforaminal lumbar interbody fusion.

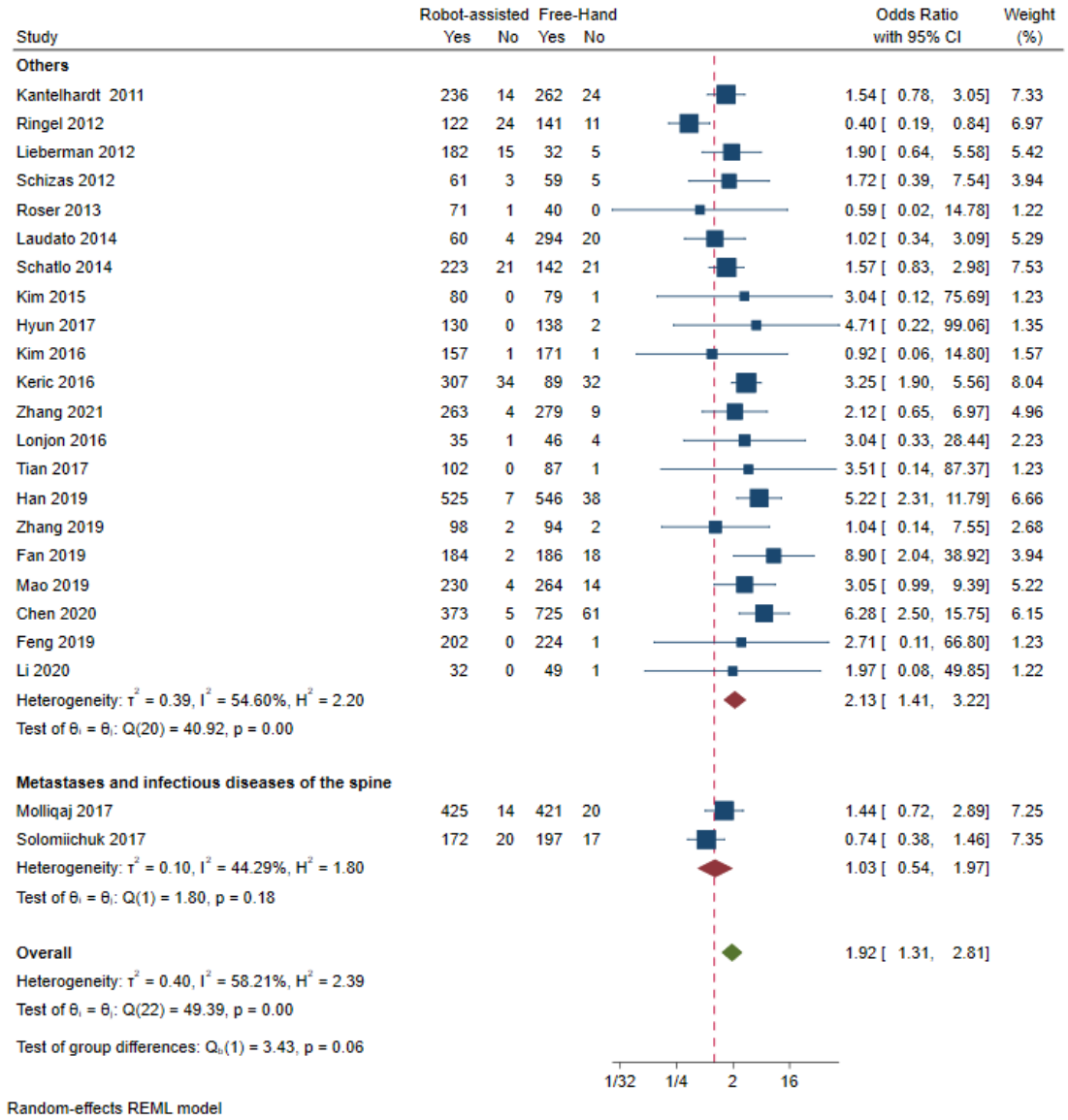
Supplementary Figure 24. Pooled analysis of per screw time.



Supplementary Figure 25. Subgroup analysis of perfect pedicle screw insertion in patients with metastases, tumor and infectious diseases of the spine.



Supplementary Figure 26. Subgroup analysis of clinically acceptable pedicle screw insertion in patients with metastases and infectious diseases of the spine.



Supplementary Table 1. Search strategy

Database	Search strategy
Pubmed	#1 "Spine"[MeSH Terms] OR "Vertebral Column"[All Fields] OR "Vertebral Columns"[All Fields] OR "Spinal Column"[All Fields] OR "Spinal Columns"[All Fields] OR "Spine"[All Fields] OR "Vertebra"[All Fields] OR "Vertebrae"[All Fields] #2 "Robotics"[MeSH Terms] OR "robot"[All Fields] OR "robotics"[All Fields] OR" robotic"[All Fields] #3 #1 AND #2
Embase	#1 "Vertebral Column"[All Fields] OR "Vertebral Columns"[All Fields] OR "Spinal Column"[All Fields] OR "Spinal Columns"[All Fields] OR "Spine"[All Fields] OR "Vertebra"[All Fields] OR "Vertebrae"[All Fields] #2 "robot"[All Fields] OR "robotics"[All Fields] OR" robotic "[All Fields] #3 #1 AND #2
Cochrane library	#1 "Vertebral Column"[TI,AB,KW] OR "Vertebral Columns"[TI,AB,KW] OR "Spinal Column"[TI,AB,KW] OR "Spinal Columns"[TI,AB,KW] OR "Spine"[TI,AB,KW] OR "Vertebra"[TI,AB,KW] OR "Vertebrae"[TI,AB,KW] #2 "robot"[TI,AB,KW] OR "robotics"[TI,AB,KW] OR" robotic"[TI,AB,KW] #3 #1 AND #2

Supplementary Table 2. Inclusion/exclusion criteria of literature.

PICOS	Inclusion	Exclusion
P	patients with spinal disorders that underwent pedicle screw placement were included in our study	Patients younger than 18 years old.
I	1) patients in the case- or experimental group received robotic-assisted pedicle screw implantation surgery; 2) No limit on sample size.	Other types of minimally invasive technique were excluded.
C	patients in the control groups underwent conventional freehand approach.	Did not differentiate between single-level and multilevel surgery were not eligible.
O	1) Primary outcomes including accuracy of pedicle-screw placement, proximal joint violation, and complications. 2) Secondary outcome included radiation time, radiation exposure and surgical time.	Relevant outcomes were missing.
S	RCTs, prospective cohort studies, and retrospective comparative studies in our analysis.	1) Articles without peer-reviewed or unpublished; 2) Studies that were repeatedly published or had qualitative outcomes; 3) Quasi-experimental studies and crossover studies.

Supplementary Table 3. Risk of bias table.

1	Random sequence generation (selection bias)
2	Allocation concealment (selection bias)
3	Blinding of participants and personnel (performance bias)
4	Blinding of outcome assessment (detection bias)
5	Incomplete outcome data (attrition bias)
6	Selective reporting (reporting bias)
7	Other bias

Supplementary Table 4. Newcastle-Ottawa quality assessment scale.

Selection
1. Representativeness of the exposed cohort
a) Truly representative of the average_____(describe) in the community.
b) Somewhat representative of the average in the community.
c) Selected group of the users eg. Nurses, volunteers.
d)No description of the derivation of the cohort.
2. Selection of the non exposed cohort
a) Drawn from the same community as the exposed cohort.
b) Drawn from a different source.
c) No description of the derivation of the non exposed cohort.
3. Ascertainment of exposure
a) Secure record (eg. Surgical records).
b) Structured interview.
c) Written self report.
d) No description.
3. Demonstration that outcome of interest was not present at start of study
a) Yes.
d) No.
Comparability
3. Comparability of the cohorts on the basis of the design or analysis
a) Study controls for_____(select the most important factor).
b) Study controls for any additional factor (This criteria could be modified to indicate specific control for a second important factor).
Outcome
1. Assessment of outcome

a) Independent blind assessment.
b) Record linkage.
c) Self report.
a) No description.
2. Was follow up long enough for outcomes to occur
a) Yes (select an adequate follow up period for outcome of interest).
b) No.
3. Adequacy of follow up of cohorts
a) Complete follow up-all subjects accounted for.
b) Subjects lost to follow up unlikely to introduce bias.
c) Follow up rate <10% and no description of those lost.
d) No statement.

Supplementary Table 5. Scores of the Newcastle-Ottawa quality assessment scale for 16 cohort studies.

Study	Selection	Comparability	Outcome	Total
Kantelhardt 2011	★★★	★★	★★★	★★★★★★★★
Lieberman 2012	★★★	★	★★★	★★★★★★★
Schizas 2012	★★★	★	★★★	★★★★★★★
Cannestra 2014	★★★	★	★★	★★★★★★
Laudato 2014	★★★★	★★	★★★	★★★★★★★★★
Schatlo 2014	★★★	★	★★★	★★★★★★★
Zahrawi 2014	★	-	★★	★★★
Lonjon 2016	★★★	★★	★★★	★★★★★★★★
Keric 2016	★★★	★	★★★	★★★★★★★
Molliqaj 2017	★★★★	★★	★★★	★★★★★★★★★
Solomiichuk 2017	★★★★	★★	★★★	★★★★★★★★★
Archavlis 2018	★★★★	★★	★★★	★★★★★★★★★
Mao 2019	★★★★	★★	★★★	★★★★★★★★★
Zhang 2019	★★★	★★	★★★	★★★★★★★★
Chen 2020	★★★★	★★	★★★	★★★★★★★★★
Zhang 2021	★★★★	★★	★★★	★★★★★★★★★

Supplementary Table 6. Characteristics of the included trials and participants.

Number	Studies	Country	Type of study	Age (yr)		Male/ Female		Total no. of patient	Pedicle screws	Robot type	Indications	The evaluation criteria of accuracy	Images	Screw accuracy	Clinical outcome
				RA	FH	RA	FH								
1	Kantelhardt 2011	Germany	RCS	62.8	63.4	25/30	27/30	RA: 55 FH: 57	RA: 250 FH: 286	SpineAssist (Mazor)	Spinal fusion in the thoracic and lumbar spine	Category A, fully contained within the pedicle; category B, a breach less than 2 mm; category C, a breach of 2 to 4 mm; and category D, a breach greater than 4 mm.	CT	CT 2mm	Revision of screws, duration of hospitalizations, infections, CSF fistula, Adverse events, time for surgery, opioid administration.
2	Lieberman 2012	USA	RCCS	NA	NA	NA	NA	RA: 10 FH: 2	RA: 197 FH: 37	SpineAssist (Mazor)	Cadaveric Spine	Category A, fully contained within the pedicle; category B, a breach less than 2 mm; category C, a breach of 2 to 4 mm; and category D, a breach greater than 4 mm.	CT	CT 2 mm	Radiation level, fluoroscopy time, and procedure time.
3	Ringel 2012	Germany	RCT	68	67	14/16	12/18	RA: 30 FH: 30	RA: 146 FH: 152	SpineAssist (Mazor)	Mono- or bi-segmental lumbar or lumbosacral stabilization	Gertzbein and Robbins scale	CT	CT 2mm	Postoperative screw revision, hospitalization, radiation exposure, and duration of surgery.
4	Schizas 2012	Switzerland	PCS	65	66	6/ 5	11/ 12	RA: 11 FH: 23	RA: 64 FH: 64	SpineAssist (Mazor)	Vertebral fracture, spinal stenosis, degenerative disc disease	Grade A = completely in; Grade B = < 2 mm breach; Grade C = 2-4 mm breach; Grade D = > 4 mm breach	CT	CT 2mm	Complications, screw revisions., radiation doses, duration of radiation.
5	Roser 2013	Germany	RCT	NA	NA	NA	NA	RA: 18 FH: 10	RA: 72 FH: 40	SpineAssist (Mazor)	Monosegmental degenerative lumbar instability	Gertzbein and Robbins	CT	CT 2mm	Radiation dosage, radiation time.
6	Cannestra 2014	USA	RCS	NA	NA	NA	NA	RA: 51 FH: 51	RA: 280 FH: 270	NA	Degenerative spine	NA	NA	NA	Complications, radiation exposure.
7	Laudato 2014	Switzerland	RCS	NA	NA	NA	NA	RA: 11 FH: 48	RA: 64 FH: 314	SpineAssist (Mazor)	NA	Grade A = completely in; Grade B = < 2 mm breach; Grade C = 2-4 mm breach; Grade D = > 4 mm breach	CT	CT 2mm	Complications, screw revision.
8	Schatlo 2014	Germany	RCS	52	58	26/ 29	12/ 28	RA: 55 FH: 40	RA: 55 FH: 40	SpineAssist (Mazor)	Degenerative spine disease	Gertzbein and Robbins scale	CT	CT 2mm	Screw revision, complication, opioid administration, blood loss, duration of operation, length of stay.
9	Zahrawi 2014	USA	RCS	NA	NA	NA	NA	RA: 52 FH: 70	RA: 253 FH: 383	Renaissance (Mazor)	Degenerative spine disease	NA	CT	CT 2 mm	Postoperative complication rates, revisions surgery, length of stay, duration of surgery, ODI, blood loss, screw implantation time.
10	Kim 2015	South Korea	RCT	64.4	64.7	11/ 9	12/ 8	RA: 20 FH: 20	RA: 80 FH: 80	Renaissance (Mazor)	Lumbar spinal stenosis	Gertzbein and Robbins scale	CT	CT 2mm	None.
11	Lonjon 2016	France	RCS	63.4	63.4	4/6	4/ 6	RA: 10 FH: 10	RA: 40 FH: 50	ROSA	Degenerative lumbar disease	Gertzbein and Robbins scale	C-arm	CT 2mm	Duration of surgery, time in the operating room, total dose of radiation, radiation exposure, instrumentation level.
12	Keric 2016	Germany	RCS	72.3	68	36/30	13/11	RA: 66 FH: 24	RA: 341 FH: 121	Renaissance (Mazor)	Pyogenic spondylodiscitis of the lumbar and thoracic spine	Screws entirely in the bone were graded 0, encroachment of the cortical bone grade 1, deviation of less than 3 mm grade 2, deviation from 3 to 6 mm grade 3, and deviation of more than 6 mm grade 4	CT	CT 2mm	Postoperative hospitalization, pain, screw revisions, quality of life, ODI.
13	Kim 2016	South Korea	RCT	65.4	66.0	19/ 18	22/ 19	RA: 37 FH: 41	RA: 158 FH: 172	Renaissance (Mazor)	Lumbar spinal stenosis	Gertzbein and Robbins scale	CT	CT 2mm	Duration of surgery, complications, radiation exposure, time to return to ambulation.
14	Hyun 2017	South Korea	RCT	66.5	66.8	9/ 21	8/ 22	RA: 30 FH: 30	RA: 130 FH: 140	Renaissance (Mazor)	Degenerative lumbar disease	Gertzbein and Robbins scale	CT	CT 2mm	Postoperative screw revision, hospitalization, radiation exposure, pain, quality of life and complications.
15	Molliqaj 2017	Germany	RCS	58.3	54.4	50/ 48	36/ 35	RA: 98 FH: 71	RA: 439 FH: 441	SpineAssist (Mazor)	Degenerative, trauma and tumor	Gertzbein and Robbins scale	CT	CT 2mm	Complications, screw revisions.
16	Solomiichuk 2017	Switzerland	RCS	63.7	62.2	21/ 14	23/ 12	RA: 35 FH: 35	RA: 192 FH: 214	SpineAssist (Mazor)	Metastatic spine disease	Gertzbein and Robbins scale	CT	CT 2mm	Complications, radiation exposure, radiation time, surgicalsite infection.

17	Tian 2017	China	RCT	NA	NA	NA	NA	RA: 23 FH: 17	RA: 102 FH: 88	TiRobot (TINAVI)	Lumbar vertebral fracture, lumbar spondylolisthesis	Gertzbein and Robbins scale	C-arm	CT 2mm	Duration of operation.
18	Archavlis 2018	Germany	RCS	51	49	22/ 36	32/ 40	RA: 58 FH: 72	RA: 116 FH: 144	Renaissance (Mazor)	Degenerative spondylolisthetic stenosis grades I and II and degenerative disease	NA	CT	CT	Facet joint violation.
19	Han 2019	China	RCT	54.6	56.1	55/60	58/61	RA:115 FH:119	RA: 532 FH: 584	TiRobot (TINAVI)	Degenerative and trauma	Gertzbein and Robbins scale	C-arm	CT 2mm	Duration of surgery, length of hospital stay, proximal joint violation, and revision surgery.
20	Mao 2019	China	PCS	55.1	59.2	18/ 39	25/ 34	RA:57 FH:59	RA: 234 FH: 278	TiRobot (TINAVI)	Degenerative lumbar disease	Gertzbein and Robbins scale	C-arm	CT 2mm	Operation time, blood loss, radiation time, radiation dosage, postoperative hospitalization, adverse events, revisions.
21	Fan 2019	China	RCT	49	49.5	31/ 18	39/ 27	RA:61 FH:66	RA: 186 FH: 204	TiRobot (TINAVI)	Cervical spinal disease	Gertzbein and Robbins scale	C-arm	CT	Duration of surgery, blood loss, postoperative length of stay, and surgery related complications.
22	Feng 2019	China	RCT	67.55	67.88	12/ 28	13/ 27	RA:40 FH:40	RA: 202 FH: 225	TiRobot (TINAVI)	Degenerative lumbar disease with osteoporosis	Gertzbein and Robbins scale	C-arm	CT 2mm	Operative time, pedicle screw placement time, radiation exposure to the medical team, and intraoperative blood loss were recorded
23	Zhang 2019	China	PCS	54.6	55.6	17/ 33	21/ 29	RA: 50 FH: 50	RA: 100 FH: 96	TiRobot (TINAVI)	Lumbar degenerative disease	Gertzbein and Robbins scale	C-arm	CT 2mm	Facet-joint violation, pedicle, surgical time, intraoperative blood loss, length of stay, revision surgery, radiation exposure.
24	Chen 2020	China	RCS	69.8	69.3	12/19	25/41	RA: 31 FH: 66	RA: 378 FH: 786	TiRobot (TINAVI)	Adult degenerative scoliosis	Gertzbein and Robbins scale	C-arm	CT 2mm	Operative time, intraoperative blood loss, length of stay, adverse events, revisions.
25	Li 2020	China	RCT	47.4	49.9	3/4	4/6	RA: 7 FH: 10	RA: 32 FH: 50	Orthbot	Degenerative lumbar disc disease or lumbar spinal stenosis	Gertzbein and Robbins scale	CT	CT 1 mm	operation time, blood loss, radiation time (radiation time per case and per screw), length of stay, and screw-related complications.
26	Zhang 2021	China	RCS	65.95	66.86	21/ 18	22/ 20	RA: 39 FH: 42	RA: 32 FH: 50	Renaissance (Mazor)	Patients underwent lumbar surgery before, and needed revision surgery	Gertzbein and Robbins scale	CT	NA	Operative time, intraoperative blood loss, intraoperative fluoroscopy time, complications.

RA: robot-assisted; FH: free hand; RCT: randomized controlled trial; RCS: retrospective cohort study; PCS: prospective cohort study; RCCS: retrospective cadaveric cohort study. CT: computed tomography. Gertzbein and Robbins scale：Screw position was classified within the pedicle (group A), cortical breach of less than 2 mm (group B), cortical breach of 2 mm or more but less than 4 mm (group C), cortical breach of 4 mm or more but less than 6 mm (group D), and cortical breach of 6 mm or more (group E).