



Early national comparison of robotic versus conventional knee replacements for arthritis using National Joint Registry data: target trial emulation study

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Additional material is published
online only. To view please visit
the journal online.

Cite this as: *BMJ* 2026;394:e100691
<http://dx.doi.org/10.1136/bmj-2026-100691>

Accepted: 25 August 2026

ABSTRACT

OBJECTIVE

To evaluate the early comparative effectiveness of robotic versus conventional total knee replacement (TKR) and unicompartmental knee replacement (UKR) in the UK.

DESIGN

Target trial emulation study.

SETTING

Public and private hospitals using data from the National Joint Registry of England, Wales, Northern Ireland, the Isle of Man, Guernsey, and Jersey.

PARTICIPANTS

697 145 knee replacement surgeries between 2018 and 2024: 675 034 were conventional (TKRs and UKRs) and 22 111 were robotic.

MAIN OUTCOME MEASURES

The main outcome was five year knee replacement survival (mean 2.5 years follow-up); all cause revision risk; cause specific revision risk; intraoperative complications; and revision complexity of robotic versus conventional (TKR and UKR) knee replacement. Kaplan-Meier and Cox regression analyses were used to compare implant survival and indications for revision surgery. Propensity score matching using target trial emulation framework was used to estimate the average treatment effect in the treated population.

RESULTS

The five year implant survival of the matched conventional and robotic TKR groups was 98.5% (95% confidence interval (CI) 98.3% to 98.7%) and 98.6% (98.2% to 99.0%), respectively, with no between group difference in revision risk (hazard ratio 1.03, 95% CI 0.86 to 1.26; P=0.71). The five year implant

survival of the matched conventional and robotic UKR groups was 97.8% (95% CI 97.2% to 98.3%) and 96.4% (92.4% to 98.3%), respectively, with no between group difference in revision risk (hazard ratio 1.03, 95% CI 0.75 to 1.42; P=0.86). Cause specific revision risk and intraoperative complication risks did not differ between groups for either TKR or UKR.

CONCLUSIONS

No statistically significant differences were detected in revision risk, cause specific risk, or intraoperative complication risk between the robotic and conventional groups. This was consistent for both TKR and UKR. The possibility of unmeasured and residual confounding cannot be ruled out, however, owing to the observational design of the study. These results highlight the importance of careful evaluation of robotic technology in publicly funded healthcare systems, given the substantially higher capital and procedural costs involved.

Introduction

Knee replacement is the main treatment for end stage knee arthritis. More than 100 000 knee replacements are performed annually in the UK, and this number is projected to increase as a result of an ageing population and high prevalence of risk factors such as obesity.^{1 2} One in five patients are dissatisfied after knee replacement surgery,³ and between 5% and 10% of patients require revision surgery with a new implant because of unacceptable outcomes.¹ Revision surgery within the first two years after knee replacement surgery dominates, mainly due to early loosening and malpositioning of implants.⁴

Robotic surgery was introduced to improve the positioning of femoral and tibial implants and should theoretically reduce the early revision risk of knee replacements. Robotic systems use preoperative and intraoperative imaging to help guide surgeons to place implants more accurately. Positioning an implant more accurately might also improve longer term risks of revision surgery and improve knee function.

The uptake of robotic technology has been rapid worldwide. The NHS recently published its 10 year plan to use robotic surgery to improve patient care,⁵ aiming for a sevenfold increase in such surgeries by 2035.⁶ Robotic systems cost around £1.0m (\$1.4m; €1.2m) to implement initially,^{7 8} followed by an increased cost per patient of about £1000-£2500.^{9 10} If robotic systems were used for all knee replacements in the NHS, the additional cost would be at least £100m extra annually.

It is currently unknown whether robotic surgery for knee replacements improves clinical outcomes. The

WHAT IS ALREADY KNOWN ON THIS TOPIC

The NHS has announced plans for a sevenfold increase in robotic surgeries by 2035
Robotic assisted knee replacement improves implant positioning, but it is unclear whether this translates into better outcomes and reduced revision risk
The National Institute for Health and Care Excellence has recommended urgent research to study the effect of robotic surgery on revision risk after joint replacement

WHAT THIS STUDY ADDS

Robotic assisted surgery was not associated with lower early overall or cause specific revision risk (consistent for both total and partial knee replacements)
Intraoperative complications and revision complexity did not differ between robotic and conventional procedures
These early findings provide real world evidence during planned rapid NHS adoption of robotic surgery

National Institute for Health and Care Excellence has highlighted an urgent need for research into robotic orthopaedics focused on the risk of failure.¹¹ Existing studies comprised single centre designs with small patient groups.^{12 13} RACER-Knee (Robotic Arthroplasty Clinical and Cost Effectiveness-Knee), a UK randomised controlled trial comparing conventional with robotic knee replacement surgery, has just published its one year results showing no significant differences in patient reported outcome measures between groups.^{7 10} However, it is not feasible for clinical trials to evaluate the rare complications of joint failure resulting in revision surgery, infection, and surgical complications.

As the NHS is currently discussing procurement of robotic systems, answers are needed on how the early failure and mortality risks compare between robotic and conventional surgery. The National Joint Registry of England, Wales, Northern Ireland, the Isle of Man, Guernsey, and Jersey is a large orthopaedic registry that collects information on all joint replacements performed in the UK outside of Scotland.¹ We used this nationwide data to study whether patients have any benefit from robotic knee replacement surgery compared with conventional surgery.

Methods

Data sources

The National Joint Registry, established in April 2003, contains records on more than two million joint

replacements.¹ Case ascertainment is 99.6% and linkage to follow-up procedures is 95%.¹⁴ Mortality data were provided from the Office for National Statistics. The data collected in the registry were designed to capture factors that influence revision surgery. Data collection forms are available on the National Joint Registry website.¹⁵

Design

We obtained retrospective observational data from the National Joint Registry between 1 January 2018 (year in which the first robotic procedure was recorded) and 31 December 2024. Using a target trial emulation design,¹⁶ we compared the effectiveness of robotic knee surgery with conventional surgery using the endpoints of revision risk and cause specific revision risk. This approach uses the design principles of a hypothetical randomised controlled trial and applies these to routine data (see table 1).¹⁶ Our estimand was the average treatment effect in the treated population. In another analysis, we also assessed the average treatment effect for a different, wider, target population.

Analyses were performed separately for total knee replacements (TKRs) and unicompartmental knee replacements (UKRs) because of differences in inherent revision risk,¹ effect size of confounders,¹⁷ and differences in surgical indications or patient selection^{18 19} between groups. A directed acyclic graph

Table 1 | Details of target trial emulation design applied to study dataset

	Target trial protocol	Emulation of target trial using real world data
Eligibility criteria	Inclusion: adults (>18 years) with primary knee replacements. Both TKR and UKR included and will be analysed separately. All indications for surgery will be included (osteoarthritis, rheumatoid arthritis, and avascular necrosis) Exclusion: non-primary knee replacements	Inclusion: adults (>18 years) with primary knee replacements. Both TKR and UKR to be included. All indications for surgery will be included (osteoarthritis, rheumatoid arthritis, and avascular necrosis) Exclusion: non-primary knee replacements, patients who did not give consent to the National Joint Registry to use their data for research
Treatment strategies	Conventional knee replacement (control), versus robotic knee replacement (intervention). All robotic systems in use in the UK will be included	Same as target trial
Treatment assignment	Patients who meet inclusion criteria are randomised to each surgical arm at 1:1 ratio. Clinicians are not, but patients and analysts are, masked to the surgical allocation In a randomised controlled trial, randomisation ensures that any difference in outcomes is attributable to the effect of treatment and so represents the causal effect of treatment in the study population (average treatment effect in treated and untreated individuals)	Randomisation emulated using propensity score methods (propensity score matching and inverse probability of treatment weights to balance groups according to known and measured confounders Propensity score matching to estimate average treatment effect in the treated population The inverse probability of treatment weighting estimates the average treatment effect in the entire population (average treatment effect) and not treated individuals only
Follow-up	Start (time zero): time of treatment allocation (randomisation). Baseline is when a patient is randomised before undergoing surgery on the day of surgery End: patients will be followed up from baseline until date of death, loss to follow-up (last date of contact with the service provider), or end of study period (last date of data collection), whichever comes first	Start (time zero): initiation of treatment (date of surgery) End: same as target trial
Outcomes	All outcomes collected at 1, 2, 3, 4, and 5 years postoperatively Primary: implant survival and revision surgery risk Secondary: indications for revision surgery and intraoperative complications	Same as target trial
Estimands	Effect of receiving robotic versus conventional knee replacement Clinical outcomes: revision risk and indications for revision compared between groups using hazard ratios	Effect of receiving robotic versus conventional knee replacement and are retained in the matched analyses Clinical outcomes: revision risk and indications for revision compared between groups using hazard ratios
Statistical analysis	Multivariable regression models (Cox for time to event, logistic for binary outcome). As patients receive surgery, no requirement to further adjust for factors associated with adherence In a randomised controlled trial, randomisation ensures that any difference in outcomes is attributable to the effect of treatment and so represents the causal effect of treatment in the study population (average treatment effect in treated and untreated individuals)	Same as target trial with adjustment for baseline confounders using propensity score methods Propensity score matching to estimate average treatment effect in the treated population The inverse probability of treatment weighting estimates the average treatment effect in the entire population (average treatment effect) and not treated individuals only

TKR=total knee replacements; UKR=unicompartmental knee replacement.

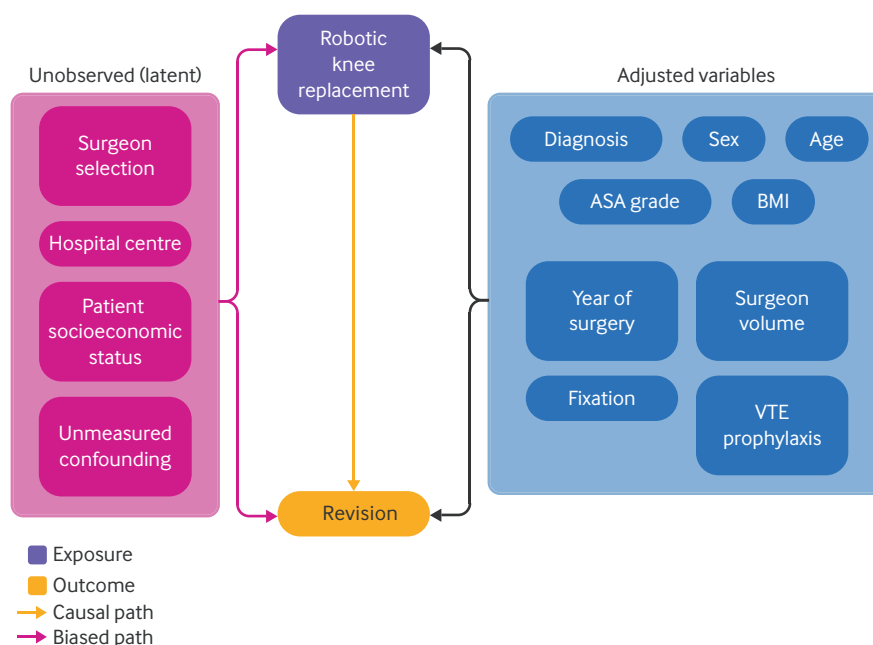


Fig 1 | Directed acyclic graph. The arrow from robotic knee replacement to revision represents the total effect that will be mediated through factors such as implant position, soft tissue balance, gait, and surgical skill. Arrows between the nodes representing baseline covariates are not shown. ASA=American Society of Anesthesiologists; BMI=body mass index; VTE=venous thromboembolism

was used to visualise measured and unmeasured confounders for surgery type and outcome (fig 1).

Interventions and outcomes

The interventions comprised robotic knee replacement surgery and conventional surgery. Revision surgery (all cause) was defined as any implant component removed, exchanged, or added since the original operation. Cause specific revisions were those involving specific indications. Secondary outcomes were intraoperative complications and complexity of the revision surgery. Two stage revision procedures are when more than one operation is needed to correct the failed knee replacement.

Propensity score matching and rationale

We examined model parameters using routine statistical summaries of central tendency and variance to identify baseline imbalance between conventional and robotic groups. Because of the potential for confounding, we a priori matched conventional and robotic groups for known confounders using propensity scores. We specifically matched on the covariates of age, sex, diagnosis, ASA (American Society of Anesthesiologists) physical status grade, implant fixation, year of surgery, prophylaxis for venous thromboembolism, and surgeon caseload (number of knee replacements performed annually). Table 2 describes the rationale for using these covariates. We did not match on body mass index (BMI) in our primary analysis owing to missing data

(17%) but included BMI as a covariate matched on a sensitivity analysis for patients with complete data. Logistic regression was used to generate a propensity score for the probability that a patient received a robotic knee replacement. We used an algorithm that matched on the logit of the propensity score with a 0.02 standard deviation (SD) calliper width. The matching ratio was 4:1 given the excess numbers of conventional knee replacements. A maximum of four controls for each patient were selected, as additional controls beyond this are known to have a limited benefit of further improving precision and power.²⁰ We used greedy matching without replacement.²¹ To assess any covariate imbalance between conventional and robotic groups, we examined standardised mean differences both before and after matching, with differences $\geq 10\%$ considered suggestive of imbalance.²²

Statistical analyses

Cumulative survival functions were determined using the Kaplan-Meier method. The endpoint for implant survival was revision surgery. Cox regression models were used to generate hazard ratios for implant survival between conventional and robotic groups. To assess the assumption of proportional hazards in the Cox regression models, we used Schoenfeld residuals to test for evidence of departure from proportionality. We found no evidence of non-proportional hazards in all analyses presented. Hazard ratios >1 indicated higher risk in the robotic group. Results remained unchanged when we tested a robust variance estimator in

Table 2 | List of confounders matched on, rationale for selection, and evidence on outcomes

Variable	Why confounder for TKR	Why confounder for UKR
Sex		
Relation to exposure	Female patients are more likely to be offered robotic surgery as they have smaller knees than male patients meaning more technically challenging cuts that would benefit from robotic surgery. In addition, female patients are more likely to have osteoporotic bone making the cuts more challenging and suitable for robotic surgery	Female patients are more likely to be offered robotic surgery as on average they have smaller knees than male patients meaning more technically challenging cuts that would benefit from robotic surgery. In addition, female patients are more likely to have osteoporotic bone making the cuts more challenging and suitable for robotic surgery
Evidence of impact on outcomes	Higher revision rates are associated with male sex ^{32 33}	Higher revision rates are associated with female sex ³⁴
Age		
Relation to exposure	Younger patients are more likely to be offered robotic surgery given their greater activity and longer life expectancy. Therefore, surgeons are more likely to offer robotic surgery to get the best implant positioning possible. Younger patients are also more likely to be amenable to new technology	Younger patients are more likely to be offered robotic surgery given their greater activity and longer life expectancy. Therefore, surgeons are more likely to offer robotic surgery to get the best implant positioning possible. Younger patients are also more likely to be amenable to new technology
Evidence of impact on outcomes	Higher revision rates are associated with younger patients ³²	Higher revision rates are associated with younger patients. Younger patients have a higher risk of aseptic loosening ³⁴
ASA grade		
Relation to exposure	Patients with lower ASA grades are more likely to be offered robotic surgery. Fitter patients are deemed better candidates given the time taken for robotic calibration. In addition, if calibration is lost intraoperatively the surgeon needs to convert to conventional surgery, which would be a risk in patients considered at high risk from anaesthetic	Patients with lower ASA grades are more likely to be offered robotic surgery. Fitter patients are deemed better candidates given the time taken for robotic calibration. In addition, if calibration is lost intraoperatively the surgeon needs to convert to conventional surgery, which would be a risk in patients considered at high risk of anaesthetic
Evidence of impact on outcomes	Higher risk of revision with higher ASA grade ³⁵	Higher ASA grades are associated with higher revision rates for UKR ³⁴
Body mass index		
Relation to exposure	Patients with a higher body mass index are more likely to be offered robotic surgery owing to issues with exposure and visualisation	Patients with a higher body mass index are less likely to be offered robotic surgery owing to issues with exposure and visualisation
Evidence of impact on outcomes	Higher risk of revision with higher body mass index ³⁶	Higher risk of revision with higher body mass index ³⁷
Surgeon caseload		
Relation to exposure	Higher volume surgeons more likely to use robotic TKRs. They are more confident to convert to conventional knee replacement when issues with calibration arise	Higher volume surgeons more likely to use robotic UKRs. They are more confident to convert to conventional knee replacement when issues with calibration arise
Evidence of impact on outcomes	Higher volume surgeons have better clinical outcomes and lower revision rates ^{38 39}	Higher volume surgeons have better clinical outcomes ¹⁷
Year of surgery		
Relation to exposure	More likely to have robotic TKR in recent years given expansion of robotics programme in the NHS	More likely to have robotic UKR in recent years given expansion of robotics programme in the NHS
Evidence of impact on outcomes	Revision rates for joint replacements have decreased in more recent years ⁴⁰	Revision rates for joint replacements have decreased in more recent years ⁴⁰
Surgical fixation		
Relation to exposure	Most robotic systems in the UK are set up for cemented TKRs	Most robotic systems in the UK are set up for cemented UKRs
Evidence of impact on outcomes	Higher revision rates for cementless TKRs ⁴¹	Higher revision rates for cemented UKRs ⁴²
Diagnosis		
Relation to exposure	Patients with inflammatory arthritis are less likely to receive robotic surgery owing to perceived increased risk of surgical site infections from pin site incisions and time taken for robotic calibration	Patients with inflammatory arthritis are less likely to receive robotic surgery owing to perceived increased risk of surgical site infections from pin site incision and time taken for robotic calibration
Evidence of impact on outcomes	Inflammatory arthritis associated with higher risk of revision and infection ^{33 43 44}	Inflammatory arthritis associated with higher risk of revision and infection ^{43 44}
VTE prophylaxis		
Relation to exposure	Patients without chemical and mechanical VTE prophylaxis may be deemed more mobile and lower risk making them more likely to receive robotic surgery Patients on both chemical and mechanical VTE prophylaxis could be deemed as higher VTE risk from other comorbidities and therefore could be less likely to receive robotic surgery given increased time for intraoperative robotic calibration	Patients without chemical and mechanical VTE prophylaxis may be deemed more mobile and lower risk making them more likely to receive robotic surgery Patients on both chemical and mechanical VTE prophylaxis could be deemed as higher VTE risk from other comorbidities and therefore could be less likely to receive robotic surgery given increased time for intraoperative robotic calibration
Evidence of impact on outcomes	VTE prophylaxis associated with increased risk of surgical site infection ⁴⁵	VTE prophylaxis associated with increased risk of surgical site infection ⁴⁵

ASA=American Society of Anesthesiologists; TKR=total knee replacement; UKR=unicompartmental knee replacement; VTE=venous thromboembolism.

regression models to account for clustering within the matched cohort; performed a multilevel frailty model sensitivity analysis to control for patient clustering within surgeons; and used adjusted Cox models including the covariates with residual imbalance after matching such as BMI (standardised mean difference $\geq 10\%$). Fine and Gray regression analysis was also

utilised, which considers the competing mortality risk and provides sub hazard ratios. To compare indications for revision surgery, we used Cox regression models to generate hazard ratios. The proportional χ^2 test with Yates' correction was used to compare the risk of intraoperative complications and complexity of revision surgery (risk of two stage revision) between

Table 3 | Model parameters before and after matching TKRs. Values are number (percentage) unless stated otherwise

Covariates	Unmatched cohort			Matched cohort		
	Conventional TKR (n=585 242)	Robotic TKR (n=17 431)	SMD	Conventional TKR (n=69 020)	Robotic TKR (n=17 255)	SMD
Sex:						
Female	331 540 (56.6)	9755 (56.0)	0.01	38 726 (56.1)	9682 (56.1)	<0.001
Male	253 702 (43.4)	7676 (44.0)		30 294 (43.9)	7573 (43.9)	
Mean (SD) age at surgery (years)	70.4 (9.1)	69.7 (9.2)	0.08	69.7 (9.0)	69.7 (9.2)	0.004
Mean (SD) BMI	30.9 (5.4) (n=482 672)	30.2 (5.6) (n=14 594)	0.13	30.8 (5.3) (n=57 365)	30.2 (5.6) (n=14 440)	0.12
Primary diagnosis:						
Primary OA	568 698 (97.2)	17 061 (97.9)	0.05	67 489 (97.8)	16 886 (97.9)	0.006
Rheumatoid arthritis	5007 (0.9)	95 (0.5)		397 (0.6)	95 (0.6)	
Avascular necrosis	2142 (0.4)	46 (0.3)		180 (0.3)	46 (0.3)	
Other	9395 (1.6)	229 (1.3)		954 (1.4)	228 (1.3)	
Mean (SD) surgeon caseload/year*	58.3 (44.1)	61.8 (41.2)	0.08	61.3 (48.3)	61.6 (40.9)	0.007
ASA grade:						
1	32 736 (5.6)	1341 (7.7)	0.18	5111 (7.4)	1279 (7.4)	0.004
2	418 965 (71.6)	13 233 (75.9)		52 587 (76.2)	13 119 (76.0)	
≥3	133 541 (22.8)	2857 (16.4)		11 322 (16.4)	2857 (16.6)	
VTE: chemical:						
LMWH (±other†)	340 374 (58.2)	11 252 (64.6)	0.16	44 590 (64.6)	11 090 (64.3)	0.007
Aspirin only	120 602 (20.6)	3509 (20.3)		13 879 (20.1)	3499 (20.3)	
Other	122 415 (20.9)	2608 (15.0)		10 315 (14.9)	2604 (15.1)	
None	1851 (0.3)	62 (0.4)		236 (0.3)	62 (0.4)	
VTE: mechanical:						
Any	552 405 (94.4)	16 685 (95.7)	0.06	66 148 (95.8)	16 510 (95.7)	0.008
None	32 837 (5.6)	746 (4.3)		2872 (4.2)	745 (4.3)	
Fixation:						
Cemented	535 939 (91.6)	13 600 (78.0)	0.39	54 787 (79.4)	13 600 (78.8)	0.02
Cementless	16 713 (2.9)	1661 (9.5)		5655 (8.2)	1498 (8.7)	
Hybrid	32 590 (5.5)	2170 (12.5)		8578 (12.4)	2157 (12.5)	
Year of surgery:						
2018	92 718 (15.8)	4 (0)	1.03	16 (0)	4 (0)	0.02
2019	95 674 (16.3)	73 (0.4)		285 (0.4)	73 (0.4)	
2020	44 119 (7.5)	691 (4.0)		2543 (3.7)	691 (4.0)	
2021	65 859 (11.3)	2017 (11.6)		7928 (11.5)	2016 (11.7)	
2022	83 262 (14.2)	3475 (9.9)		14 034 (20.3)	3469 (20.1)	
2023	97 101 (16.6)	4751 (27.3)		18 694 (27.1)	4718 (27.3)	
2024	106 509 (18.2)	6420 (36.8)		25 520 (37.0)	6284 (36.4)	

All variables had complete sets of data except BMI where the number is presented in brackets under the means presented.

ASA=American Society of Anesthesiologists; BMI=body mass index; LMWH=low molecular weight heparin; OA=osteoarthritis; SD=standard deviation; SMD=standardised mean difference; TKR=total knee replacement; VTE=venous thromboembolism.

*Related to primary TKR.

†Other chemical VTE agent.

the surgery groups, unless frequencies were <5 in which case Fisher's exact test was used.

Sensitivity analyses

Unmeasured confounding

E value analyses were used to quantify and transparently report the strength of an unmeasured confounder needed to alter point estimates and corresponding confidence intervals.²³

Missing body mass index

The principal missingness covariate of interest in our directed acyclic graphic was BMI (17%). We found no differences in characteristics or clinically relevant factors between all patients and patients with complete BMI data (see supplementary appendix, table S1). In a sensitivity analysis, we repeated the propensity score matching, as described previously, but included the BMI covariate in the model and therefore only included patients with complete BMI data (see supplementary appendix, tables S2 and S3).

Surgeon learning curves

A surgeon's learning curve for performing robotic knee replacement is well described as seven patients undergoing TKR²⁴ and six undergoing UKR.²⁵ We performed a sensitivity analysis in which we rematched the cohort after excluding the first 10 cases who underwent a robotic procedure for every surgeon for both TKRs and UKRs (see supplementary appendix, tables S4 and S5).⁷

Inverse probability treatment weighting analyses for full cohort

Propensity score matching estimates the average treatment effect in treated patients. This is because the closest untreated and treated individuals are matched, and the remaining untreated individuals who were not matched are excluded from the analysis. Inverse probability of treatment weighting estimates the treatment effect in a population with a distribution of risk factors equal to that for all study participants (not treated participants only).²⁶ We included the

Table 4 | Model parameters before and after matching UKRs. Values are number (percentage) unless stated otherwise

Covariates	Unmatched cohort			Matched cohort		
	Conventional UKR (n=89 792)	Robotic UKR (n=4680)	SMD	Conventional UKR (n=18 320)	Robotic UKR (n=4580)	SMD
Sex:						
Female	41 575 (46.3)	2114 (45.2)	0.02	8425 (46.0)	2077 (45.4)	0.01
Male	48 217 (53.7)	2566 (54.8)		9895 (54.0)	2503 (54.7)	
Mean (SD) age at surgery (years)	65.5 (9.9)	65.6 (9.8)	0.01	65.6 (9.8)	65.6 (9.8)	0.002
Mean (SD) BMI	30.1 (5.1) (n=75657)	29.0 (5.0) (n=3885)	0.22	29.8 (4.8) (n=15 388)	29.0 (5.0) (n=3798)	0.16
Primary diagnosis:						
Primary OA	88 610 (98.7)	4612 (98.6)	0.02	18 075 (98.7)	4520 (98.7)	0.003
Rheumatoid arthritis	29 (0.03)	1 (0.02)		4 (0.02)	1 (0.02)	
Avascular necrosis	703 (0.78)	43 (0.92)		149 (0.81)	37 (0.81)	
Other	450 (0.50)	24 (0.51)		92 (0.50)	22 (0.48)	
Mean (SD) surgeon caseload/year*	27.6 (26.5)	20.5 (13.7)	0.33	20.3 (16.5)	20.7 (13.7)	0.03
ASA grade:						
1	11 427 (12.7)	812 (17.4)	0.18	2830 (15.5)	728 (15.9)	0.01
2	67 025 (74.6)	3482 (74.4)		13 968 (76.2)	3466 (75.7)	
≥3	11 340 (12.6)	386 (8.3)		1522 (8.3)	386 (8.4)	
VTE: chemical:						
LMWH (±other†)	42 742 (47.6)	2888 (61.7)	0.29	10 837 (59.2)	2788 (60.9)	0.04
Aspirin only	26 835 (29.9)	976 (20.9)		4110 (22.4)	976 (21.3)	
Other	19 847 (22.1)	804 (17.2)		3323 (18.1)	804 (17.6)	
None	368 (0.41)	12 (0.26)		50 (0.27)	12 (0.26)	
VTE: mechanical:						
Any	84 313 (93.9)	4511 (96.4)	0.12	17 658 (96.4)	4412 (96.3)	0.003
None	5479 (6.1)	169 (3.6)		662 (3.6)	168 (3.7)	
Fixation:						
Cemented	57 827 (64.4)	4640 (99.2)	1.02	18 186 (99.3)	4540 (99.1)	0.02
Cementless	30 131 (33.6)	7 (0.15)		30 (0.16)	7 (0.15)	
Hybrid	1834 (2.0)	33 (0.71)		104 (0.57)	33 (0.72)	
Year of surgery:						
2018	11 837 (13.2)	4 (0.09)	0.89	15 (0.08)	4 (0.1)	0.02
2019	13 028 (14.5)	30 (0.64)		94 (0.51)	30 (0.66)	
2020	6867 (7.7)	234 (5.0)		931 (5.1)	234 (5.1)	
2021	10 487 (11.7)	573 (12.2)		2325 (12.7)	572 (12.5)	
2022	12 862 (14.3)	963 (20.6)		3722 (20.3)	940 (20.5)	
2023	16 151 (18.0)	1118 (23.9)		4490 (24.5)	1106 (24.2)	
2024	18 560 (20.7)	1758 (37.6)		6743 (36.8)	1694 (37.0)	

All variables had complete sets of data except BMI where the number is presented in brackets under the means presented.

ASA=American Society of Anesthesiologists; BMI=body mass index; LMWH=low molecular weight heparin; OA=osteoarthritis; SD=standard deviation; SMD=standardised mean difference; UKR=unicompartmental knee replacement; VTE=venous thromboembolism.

*Related to primary UKR.

†Other chemical VTE agent.

inverse probability of treatment weighting analyses as an additional analysis referring to a different target population, and the estimand for this analysis was the average treatment effect. A concern of inverse probability of treatment weighting is that individuals with large weights (extremely high or low probability of treatment) can introduce high variance and thereby influence results. We addressed this by trimming

patients at the extreme 1% distribution of the propensity score (see supplementary appendix, tables S6 and S7).

All statistical analyses were performed using Stata (version 15.1; StataCorp, College Station, TX) except for propensity score matching, which was performed using R (version 3.4.0; R Foundation for Statistical Computing, Vienna, Austria).

Table 5 | List of robotic systems used for TKR and UKR in the UK

Robotic system	Manufacturer and location	No (%) of surgeries	
		TKRs (n=17 431)	UKRs (n=4680)
Mako Total Knee	Stryker, USA	13 042 (74.8)	3800 (81.2)
CORI Surgical System	Smith & Nephew, UK	1623 (9.3)	573 (12.2)
ROSA	Zimmer Biomet, USA	1604 (9.2)	NA
NAVIO	Smith & Nephew, UK	747 (4.3)	212 (0.1)
VELYS Robotic Solution	Johnson & Johnson, USA	149 (0.9)	NA
SKYWALKER	MicroPort Medbot, China	13 (0.1)	NA
Other		253 (1.5)	95 (2.0)

NA=not applicable; TKR=total knee replacement; UKR=unicompartmental knee replacement.

Table 6 | Comparisons of indications for revision in TKR and UKR propensity matched cohorts. Values are number (percentage) unless stated otherwise

Revision indication	Matched TKR cohort			Matched UKR cohort		
	Conventional surgery (n=69 020)	Robotic surgery (n=17 255)	Hazard ratio (95% CI), P value*	Conventional surgery (n=18 320)	Robotic surgery (n=4580)	Hazard ratio (95% CI), P value*
Aseptic loosening	42 (0.06)	17 (0.10)	1.61 (0.92 to 2.84), 0.09	46 (0.25)	11 (0.24)	0.96 (0.50 to 1.85), 0.92
OA progression	40 (0.06)	7 (0.04)	0.70 (0.31 to 1.56), 0.39	62 (0.34)	14 (0.31)	0.91 (0.51 to 1.62), 0.74
Lysis	8 (0.01)	5 (0.03)	2.47 (0.81 to 7.54), 0.11	6 (0.03)	1 (0.02)	0.67 (0.10 to 4.54), 0.71
Pain	19 (0.03)	4 (0.02)	0.84 (0.28 to 2.46), 0.75	13 (0.07)	5 (0.11)	1.53 (0.55 to 4.30), 0.42
Infection	251 (0.36)	78 (0.45)	1.25 (0.96 to 1.60), 0.09	31 (0.17)	6 (0.13)	0.77 (0.32 to 1.86), 0.57
Periprosthetic fracture	32 (0.05)	7 (0.04)	0.87 (0.39 to 1.97), 0.74	15 (0.08)	3 (0.07)	0.83 (0.24 to 2.86), 0.77
Wear	2 (0)	0 (0)	NA	2 (0.01)	1 (0.02)	1.98 (0.18 to 21.9), 0.58
Dislocation subluxation	28 (0.04)	4 (0.02)	0.57 (0.20 to 1.62), 0.29	8 (0.04)	2 (0.04)	1.00 (0.21 to 4.69), 1.0
Stiffness	30 (0.04)	11 (0.06)	1.47 (0.74 to 2.93), 0.28	3 (0.02)	1 (0.02)	1.32 (0.14 to 12.7), 0.81
Instability	91 (0.13)	13 (0.08)	0.57 (0.32 to 1.02), 0.06	7 (0.04)	4 (0.09)	2.29 (0.67 to 7.84), 0.19
Component dissociation	3 (0)	0 (0)	NA	2 (0.01)	1 (0.02)	2.01 (0.18 to 22.2), 0.57
Malalignment	31 (0.04)	5 (0.03)	0.64 (0.25 to 1.65), 0.36	15 (0.08)	5 (0.11)	1.33 (0.48 to 3.67), 0.58
Implant fracture	0 (0)	2 (0.01)	NA	0 (0)	1 (0.02)	NA
Incorrect sizing	0 (0)	0 (0)	NA	0 (0)	0 (0)	NA
Other	22 (0.03)	6 (0.03)	1.09 (0.44 to 2.68), 0.86	6 (0.03)	5 (0.11)	3.32 (1.01 to 10.9), 0.05

*Based on Cox regression analyses.

CI=confidence interval; NA=not applicable; OA=osteoarthritis; TKR=total knee replacement; UKR=unicompartmental knee replacement.

Patient and public involvement

The authors ran public advisory group (PAG) workshops, which helped inform this study. The PAG consisted of people with lived experience of joint replacement from diverse ethnic backgrounds and ages from London. Group members were concerned about NHS plans to make robotic surgery widespread without reliable evidence. They believed that questions about robotic joint replacements should focus on key outcomes, including the risk of failure and cost effectiveness to ensure value for money. We therefore focused our article on implant survival and revision risk. The PAG favoured using routinely collected data given that this was cost effective and the data have already been collected.

Results

Overall, 1 801 799 knee replacements were performed in England, Northern Ireland, and the Isle of Man between 1 January 2004 and 31 December 2024. After data cleaning, 1 768 923 remained. As the first robotic knee procedure recorded in the National Joint Registry was in 2018, we excluded knee replacements before 2018, leaving 697 145 available for analysis. Of these, 602 673 were TKRs (585 242 conventional, 17 431 robotic) and 94 472 were UKRs (89 792 conventional, 4680 robotic). Figure 2 summarises the data cleaning process.

After propensity matching, baseline characteristics were well balanced between the robotic and conventional surgery groups (table 3 and table 4). Both matched and inverse probability of treatment weighting sensitivity analyses using the whole cohort are presented to estimate the treatments effects in treated individuals only and all study participants. The most used robotic systems were Mako Total Knee (Stryker, MI), CORI Surgical System (Smith & Nephew, Watford, UK), and ROSA (Zimmer Biomet, IN) (table 5). Most of the robotic procedures used the Mako system.

Unmatched analyses

Total knee replacement

Overall, 585 242 TKRs in the conventional group and 17 431 in the robotic group were included in the unmatched analysis. Baseline characteristics, many of which are known to affect outcomes, differed substantially between the conventional and robotic TKR groups (table 3). The mean follow-up in the conventional group was 3.7 years (SD 2.1 years) and in the robotic group was 2.5 (SD 1.2) years. The mean annual surgeon caseload for TKR was 58.3 (SD 44.1) in the conventional group and 61.8 (SD 41.2) in the robotic group.

The conventional group underwent 6679 revisions (1.1%) at a mean of 2.0 (SD 1.7) years postoperatively.

Table 7 | Comparisons of intraoperative complications in TKR and UKR propensity matched cohorts. Values are number (percentage) unless stated otherwise

Intraoperative complications	Matched TKR cohort			Matched UKR cohort		
	Conventional surgery (n=69 020)	Robotic surgery (n=17 255)	P value*	Conventional surgery (n=18 320)	Robotic surgery (n=4580)	P value*
None	68 794 (99.7)	17 209 (99.7)	0.96	18 277 (99.8)	4578 (99.9)	0.94
Fracture	65 (0.09)	17 (0.10)	0.87	12 (0.07)	0 (0)	0.14
Ligament injury	37 (0.05)	8 (0.05)	0.71	9 (0.05)	0 (0)	0.22
Patella tendon avulsion	16 (0.02)	2 (0.01)	0.56	1 (0.01)	0 (0)	1.00
Other	108 (0.16)	19 (0.11)	0.16	21 (0.11)	2 (0.04)	0.29

*Based on χ^2 test or when frequencies were <5 based on Fisher's exact test.

TKR=total knee replacement; UKR=unicompartmental knee replacement.

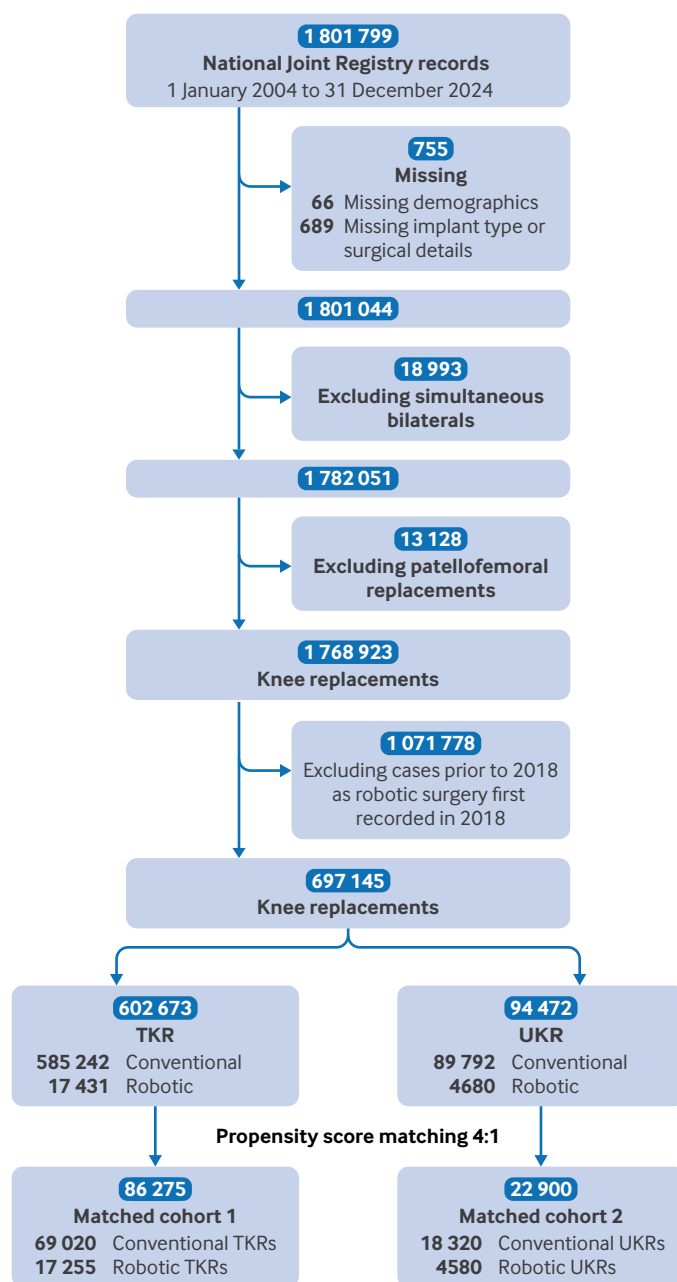


Fig 2 | Data flowchart of dataset cleaning and merging. TKRs=total knee replacements; UKRs=unicompartmental knee replacements

The robotic group underwent 134 revisions (0.77%) at a mean of 1.0 (SD 0.99) years postoperatively. The five year survival of implants was 98.5% (95% CI 98.4% to 98.6%) in the conventional group and 98.6% (98.2% to 99.0%) in the robotic group, with no between group difference in revision risk (hazard ratio 1.03, 95% CI 0.86 to 1.22; $P=0.77$).

Unicompartmental knee replacement

Overall, 89 792 UKRs in the conventional group and 4680 in the robotic group were included in the unmatched analysis. Baseline characteristics, many of which are known to influence outcomes,

differed substantially between the two groups (table 4). The mean follow-up was 3.5 (SD 2.1) years in the conventional group and 2.5 (SD 1.2) years in the robotic group. The mean annual surgeon caseload for UKR was 27.6 (SD 26.5) in the conventional group and 20.5 (SD 13.7) in the robotic group.

The conventional group underwent 1813 revisions (2.0%) at a mean of 2.2 (SD 1.8) years postoperatively. The robotic group underwent 46 revisions (1.0%) at a mean of 1.7 (SD 1.2) years postoperatively. The five year survival of implants was 97.3% (95% CI 97.1% to 97.4%) in the conventional group and 96.5% (92.4% to 98.4%) in the robotic group, with no significant between group differences in revision risk (hazard ratio 0.75, 95% CI 0.56 to 1.01; $P=0.05$).

Propensity score matched comparison analyses

Total knee replacement

Overall, 69 020 TKRs in the conventional group and 17 255 in the robotic group were included in the matched analysis. The mean follow-up was 2.5 (SD 1.2) years in both groups. The mean annual surgeon caseload for TKR was 61.3 (SD 48.3) in the conventional group and 61.6 (SD 40.9) in the robotic group (table 3). The conventional group underwent 509 revisions (0.74%) at a mean of 1.2 (SD 1.1) years postoperatively. The robotic group underwent 132 revisions (0.77%) at a mean of 1.0 (SD 1.0) years postoperatively. The five year survival of implants was 98.5% (95% CI 98.3% to 98.7%) in the conventional group and 98.6% (98.2% to 99.0%) in the robotic group, with no significant between group difference in revision risk (hazard ratio 1.03, 95% CI 0.86 to 1.26; $P=0.71$) (fig 3). In the Fine and Gray models, the sub hazard ratio was 1.04 (95% CI 0.86 to 1.26; $P=0.69$).

The point estimate E value for the TKR hazard ratio of 1.03 (95% CI 0.86 to 1.26) was 1.21, reflecting a stable, near null finding. The E values for the lower and upper confidence bounds were 1.60 and 1.83, respectively. To shift these boundaries and achieve a statistically significant directional outcome, an unmeasured confounder would require a minimum joint hazard ratio association of 1.60 to shift the lower confidence bound towards a potential benefit, or 1.83 to shift the upper bound towards a potential harm.

Indications for revision or intraoperative complications did not differ between the groups (table 6 and table 7).

Of the revisions in the conventional group, 440 (86.4%) were single stage revisions and 69 (13.6%) were two stage revisions. Of the revisions in the robotic group, 114 (86.4%) were single stage revisions and 18 (13.6%) were two stage revisions. The risk of two stage revisions did not differ between the groups ($P=0.88$).

The cohort characteristics for complete BMI and surgeon learning curve analyses were well balanced and are summarised in supplementary appendix tables S2 and S4. The sensitivity analyses for missing BMI data and surgeons' learning curves showed similar null effect results to the primary analyses (see supplementary appendix, tables S8 and S9).

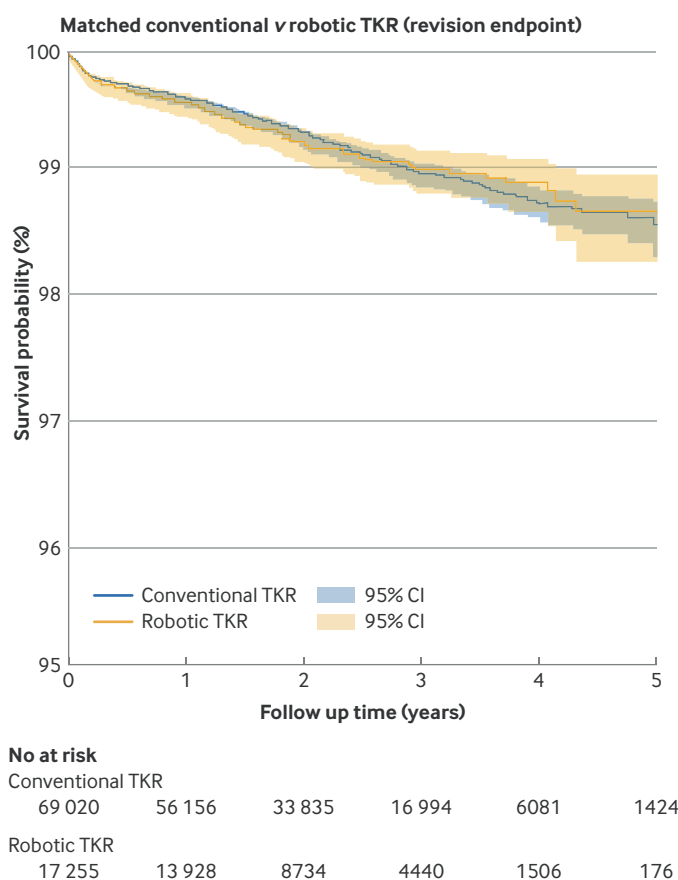


Fig 3 | Kaplan-Meier graph comparing propensity matched implant survival of robotic and conventional total knee replacements (TKRs). CI=confidence interval

Unicompartmental knee replacement

The matched analysis included 18 320 UKRs in the conventional group and 4580 in the robotic group. The mean follow-up was 2.5 (SD 1.3) years in the conventional group and 2.5 years (SD 1.5) years in the robotic group. The mean annual surgeon caseload for UKR was 20.3 (SD 16.5) in the conventional group and 20.7 (SD 13.7) in the robotic group. The conventional group underwent 179 (0.98%) revisions at a mean of 1.6 (SD 1.1) years postoperatively. The robotic group underwent 46 (1.0%) revisions at a mean of 1.7 (SD 1.2) years postoperatively. The five year survival in the conventional group was 97.8% (95% CI 97.2% to 98.3%) and in the robotic group was 96.4% (92.4% to 98.3%), with no between group difference in revision risk (hazard ratio 1.03, 95% CI 0.75 to 1.42; $P=0.86$) (fig 4). In Fine and Gray models, the sub hazard ratio was 1.03 (95% CI 0.75 to 1.43; $P=0.85$).

The point estimate E value for the UKR hazard ratio of 1.03 (95% CI 0.75 to 1.42) was 1.21, reflecting a stable, near null finding. The E values for the lower and upper confidence bounds were 2.0 and 2.19, respectively. To shift these boundaries to achieve a statistically significant directional outcome, an unmeasured confounder would require a minimum joint hazard ratio association of 2.0 to shift the lower

confidence bound towards a potential benefit, or 2.19 to shift the upper bound towards a potential harm.

Indications for revision or intraoperative complications did not differ between the groups (table 6 and table 7).

Of the revisions in the conventional group, 168 (93.9%) were single stage revisions and 11 (6.1%) were two stage revisions. Of the revisions in the robotic group, 44 (95.7%) were single stage revisions and two (4.3%) were two stage revisions. The risk of two stage revisions did not differ between the groups ($P=1.00$).

The cohort characteristics for complete BMI and surgeon learning curve analyses were well balanced and are summarised in supplementary appendix tables S3 and S5. The sensitivity analyses performed for missing BMI data and surgeons' learning curves showed similar null effect results to the primary analyses presented (see supplementary appendix, tables S8 and S9).

Inverse probability weighting analyses

In the whole cohort, 585 242 TKRs were undertaken in the conventional group and 17 431 in the robotic group. The mean follow-up was 3.7 (SD 2.1) years in the conventional group and 2.5 years (SD 1.2) in the robotic group (table 4). Baseline characteristics differed substantially between the conventional and robotic groups (table 1). Inverse probability treatment weighting with 1% trimming resulted in well balanced groups (see supplementary appendix, table S6). Revision risk did not differ between the conventional and robotic groups (hazard ratio 1.02, 95% CI 0.86 to 1.23; $P=0.76$). In Fine and Gray models, the sub hazard ratio was 1.03 (95% CI 0.86 to 1.24; $P=0.74$).

In the whole cohort, 89 792 UKRs were undertaken in the conventional group and 4680 in the robotic group. The mean follow-up was 3.5 (SD 2.1) years in the conventional group and 2.5 (SD 1.2) years in the robotic group. Baseline characteristics did not differ substantially between the conventional and robotic groups (table 1). Inverse probability treatment weighting with 1% trimming resulted in well balanced groups (see supplementary appendix, table S7). Revision risk did not differ between the conventional and robotic groups (hazard ratio 0.93, 95% CI 0.66 to 1.33; $P=0.71$). In Fine and Gray models, the sub hazard ratio was 0.94 (95% CI 0.68 to 1.29; $P=0.70$).

Discussion

This study compared differences in early revision risk between conventional and robotic surgery and included about 700 000 knee replacements in the analyses. We found no evidence of any differences in overall implant survival after robotic surgery (both TKR and UKR) compared with conventional surgery over a mean of 2.5 years and up to five years postoperatively. These findings were robust to various sensitivity analyses.

We found no differences for either TKR or UKR in cause specific revision risk or intraoperative complications between matched robotic and

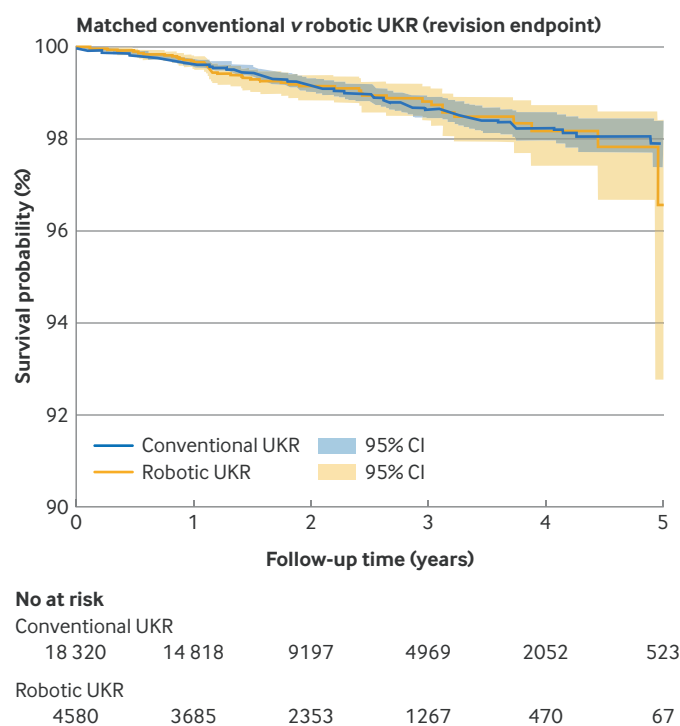


Fig 4 | Kaplan Meier graph comparing propensity matched implant survival of robotic and conventional unicompartmental knee replacements (UKRs). CI=confidence interval

conventional groups. Robotic surgery is known to improve accuracy and provide better positioning of implants.^{13 27} This in turn could lead to less pain and stiffness, better function, less joint wear, fewer fractures, and less instability. However, we found no difference in revision risk for any of these problems.

Strengths and limitations of this study

Our study has several strengths. We used a target trial emulation approach to compare clinical outcomes using a nationwide dataset with excellent case ascertainment and linkability.¹⁴ Our target trial emulation approach allowed direct comparison of similar population cohorts. All matched variables achieved a standardised mean difference <10% suggestive of covariate balance between the surgical groups for known and measured confounders. We assessed both the average treatment effect in treated (propensity matching) and the average treatment effect (inverse probability of treatment weighting analyses) estimands using different target populations and found consistent results. Our observational registry study was large enough to assess early implant survival and cause specific revision indications that are not feasible to assess in a traditional trial. Research from these studies is crucial to help guide commissioners about planning care.

The main limitation was that our study involved a retrospective observational design. We used target trial emulation with propensity score matching to estimate the average treatment effect in the treated population.

Despite matching, we could only control for known and measured confounders collected in the registry dataset. There is potential for residual confounding from unmeasured variables, including centre level effects, patient selection, surgeon preference, private versus NHS care pathways, and technology adoption bias. We were also limited by follow-up time and there may be longer term implementation effects. In addition, matching can reduce the generalisability of findings, although we were able to match virtually all the robotic knee replacements. We also performed inverse probability of treatment weighting analyses to study the wider population and obtained similar results. In addition, as we did not have patient reported outcome measures, it is not possible to know compare differences in pain and function between robotic and conventional surgery. However, the RACER-Knee trial has shown no differences in patient reported outcome measures at one year postoperatively.¹⁰ Another limitation is that despite the large size of our study, outcomes were limited due to the overall number of events, particularly for analyses of UKR and cause specific indications for revision. As some data for BMI were missing, we only matched on BMI as a complete case sensitivity analysis. Also, as there were some differences in robotic systems used, clinical heterogeneity exists. Our E value sensitivity analysis suggested that strong unmeasured confounders would be needed to explain a potential benefit or harm of robotic surgery. However, E values themselves have important limitations.

Comparison with other studies

In our trial emulation study, we aimed to appropriately compare the effectiveness of robotic TKRs compared with conventional surgery. Most current studies are limited to single centre settings with a maximum of a few hundred patients.^{13 28} Our literature review found two registry studies comparing robotic TKRs with conventional TKRs and both used data from the American Joint Replacement Registry.^{29 30} These studies also found no differences in implant survival but were limited from a data capture rate of 40% in their registry.³¹

The ongoing RACER-Knee trial has recently published its one year results showing no differences in patient reported outcome measures between robotic and conventional TKRs.¹⁰ Our observational registry study complements this trial as it is large enough to assess early implant survival, cause specific indications for revision, intraoperative complications, and severity of the revision procedure that are not feasible to assess in a clinical trial design. Research from these studies is crucial to help guide commissioners about planning care.

Policy implications

Robotic surgery is estimated to cost around £1m to deploy initially^{7 8} followed by an additional cost of about £1000-£2500 for each knee.^{9 10} This extra cost relates to preoperative scanning, additional drapes,

calibration costs, and the additional time required to perform the procedure. This cost is substantial and needs justification in a public healthcare setting. One way this could be justified is if robotic surgery improved implant survival, owing to the cost of revision procedures. On average, the cost of knee replacement revision, including postoperative care and indirect costs, is £16 000.⁹ However, our study found no differences in revision risk between surgery groups. The results of this study question the 10 year NHS plan for widespread adoption of robotics for knee replacements in the absence of a clear benefit.

Conclusions

This national study found no important differences in revision risk, cause specific risk, or intraoperative complication risk between robotic and conventional knee replacements. Findings were consistent for both TKR and UKR. Given the observational design of the study, however, we cannot rule out the possibility of unmeasured and residual confounding. These results highlight the importance of careful evaluation of robotic technology in publicly funded healthcare systems owing to the substantially higher capital and procedural costs.

We thank the patients and staff of the hospitals who contribute data to the National Joint Registry (NJR). We are grateful to the Healthcare Quality Improvement Partnership (HQIP), the NJR research committee, and staff at the NJR for facilitating this work. The authors have conformed to the NJR's standard protocol for data access and publication. The views expressed represent those of the authors and do not necessarily reflect those of the NJR steering committee, research subcommittee, or HQIP who do not vouch for how the information is presented. HRM and XLG acknowledge the support of the National Institute for Health and Care Research (NIHR) Barts Biomedical Research Centre (BRC) (NIHR203330). AJ would like to thank the NIHR Bristol BRC for its ongoing support. DWM would like to thank the NIHR Oxford BRC for its support.

Contributors: All authors contributed to the study conception and design. HRM and AJ performed data analysis. HRM is the manuscript's guarantor. All authors interpreted the data and read and approved the final manuscript. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

Funding: No specific funding received.

Competing interests: All authors have completed the ICMJE uniform disclosure form at www.icmje.org/disclosure-of-interest/ and declare: no support from any organisation for the submitted work and no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval: This study was reviewed by the Queen Mary University of London Ethics Committee and approved (reference QME25.1847).

Data sharing: Data will not be publicly available owing to restrictions imposed by the ethics committee to protect participant confidentiality. Access will require a signed data sharing agreement and institutional ethics approval where applicable. Access to the data analysed in this study required permission from the National Joint Registry research subcommittee. Information on research data access requests to the National Joint Registry is available at <https://www.njrcentre.org.uk/research/research-requests/>. No additional data are available.

Transparency: The lead author (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Dissemination to participants and related patient and public communities: The National Joint Registry and its patient representative group have been made aware of the results of this study and will support the dissemination of results through their

networks. Dissemination to the wider public will be supported by Queen Mary University of London, University of Oxford and the University of Bristol. The National Institute for Health and Care Research Biomedical Research Centre at these institutions will also support dissemination through the press, media, and charities. Surgeons and policymakers will be informed of the results through presentation at national and international scientific meetings.

Provenance and peer review: Not commissioned; externally peer reviewed.

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- 1 National Joint Registry. National Joint Registry 22nd Annual Report. National joint registry for England, Wales, Northern Ireland and Isle of Man. 2025.
- 2 Kurtz S, Ong K, Lau E, et al. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. *J Bone Joint Surg Am* 2007;89:780-5. doi:10.2106/JBJS.F.00222
- 3 Bourne RB, Chesworth BM, Davis AM, et al. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? *Clin Orthop Relat Res* 2010;468:57-63. doi:10.1007/s11999-009-1119-9
- 4 Sharkey PF, Hozack WJ, Rothman RH, et al. Insall Award paper. Why are total knee arthroplasties failing today? *Clin Orthop Relat Res* 2002;7-13. doi:10.1097/00003086-200211000-00003
- 5 Department of Health & Social Care. Fit for the future: 10 Year Health Plan for England. GOV.UK. <https://www.gov.uk/government/publications/10-year-health-plan-for-england-fit-for-the-future/fit-for-the-future-10-year-health-plan-for-england-executive-summary> 2025. [20 Aug 2026].
- 6 NHS England. Millions to benefit from NHS robot drive. <https://www.england.nhs.uk/2025/06/millions-to-benefit-from-nhs-robot-drive/#:~:text=Millions%20of%20patients%20will%20benefit,24%2C%20according%20to%20NHS%20projections.> 2025. [20 Aug 2026].
- 7 Griffin J, Davis ET, Parsons H, et al. Robotic Arthroplasty Clinical and cost Effectiveness Randomised controlled trial (RACER-knee): a study protocol. *BMJ Open* 2023;13:e068255. doi:10.1136/bmjopen-2022-068255
- 8 Griffin J, Davis ET, Parsons H, et al. UK robotic arthroplasty clinical and cost effectiveness randomised controlled trial for hips (RACER-Hip): a study protocol. *BMJ Open* 2023;13:e079328. doi:10.1136/bmjopen-2023-079328
- 9 Wrightington WaLNT. Self pay tariff 2023/2024. <https://www.wvl.nhs.uk/media/FOI/April%202024/9730%20-%20Self%20Pay%20Tariff%2023.24.pdf>. 2024. [20 Aug 2026].
- 10 Parsons H, Metcalfe A, Griffin J, et al. Robotic-arm-assisted versus conventional total knee replacement (RACER-Knee): a pragmatic, multicentre, participant-masked and assessor-masked, superiority, randomised controlled trial. *Lancet* 2026;408:924-34. doi:10.1016/S0140-6736(26)00986-4.
- 11 National Institute for Health and Care Excellence. Robot-assisted surgery for orthopaedic procedures: early value assessment. Recommendations for research. <https://www.nice.org.uk/guidance/hte22/chapter/1-Recommendations>. NICE 2025. [20 Aug 2026].
- 12 Barakat N, Ramamurti P, Duensing IM, et al. Financial Conflicts of Interest and Industry Funding are Associated With Conclusions Favorable to New Technologies: A Review of Published Economic Analyses in Hip and Knee Arthroplasty. *J Arthroplasty* 2024;39:S299-S305.e9. doi:10.1016/j.arth.2024.02.054
- 13 Mostafa O, Malik M, Qayum K, et al. Robotic-assisted versus conventional total knee arthroplasty: a systematic review and meta-analysis of alignment accuracy and clinical outcomes. *Ann Med Surg (Lond)* 2025;87:867-79. doi:10.1097/MS9.0000000000002919
- 14 National Joint Registry. Data Completeness and Quality. <https://reports.njrcentre.org.uk/Data-Completeness-and-quality#:~:text=The%20linkability%20rate%20for%202024,registry%20since%202003%20is%2094.39%25.> 2026. [20 Aug 2026].
- 15 National Joint Registry. NJR data collection forms. 2026. <https://www.njrcentre.org.uk/healthcare-providers/njr-data-collection-forms-mdsv8/>
- 16 Hernán MA, Wang W, Leaf DE. Target Trial Emulation: A Framework for Causal Inference From Observational Data. *JAMA* 2022;328:2446-7. doi:10.1001/jama.2022.21383
- 17 Liddle AD, Pandit H, Judge A, et al. Effect of surgical caseload on revision rate following total and unicompartmental knee replacement. *J Bone Joint Surg Am* 2016;98:1-8.

- 18 Willis-Owen CA, Brust K, Alsop H, et al. Unicompartmental knee arthroplasty in the UK National Health Service: an analysis of candidacy, outcome and cost efficacy. *Knee* 2009;16:473-8. doi:10.1016/j.knee.2009.04.006
- 19 Wilson HA, Middleton R, Abram SGF, et al. Patient relevant outcomes of unicompartmental versus total knee replacement: systematic review and meta-analysis. *BMJ* 2019;364:l352. doi:10.1136/bmj.l352
- 20 Kirkwood BR, Sterne JA. *Essential medical statistics*: John Wiley & sons 2010.
- 21 Austin PC. Some methods of propensity-score matching had superior performance to others: results of an empirical investigation and Monte Carlo simulations. *Biom J* 2009;51:171-84. doi:10.1002/bimj.200810488
- 22 Austin PC. Balance diagnostics for comparing the distribution of baseline covariates between treatment groups in propensity-score matched samples. *Stat Med* 2009;28:3083-107. doi:10.1002/sim.3697
- 23 VanderWeele TJ, Ding P. Sensitivity Analysis in Observational Research: Introducing the E-Value. *Ann Intern Med* 2017;167:268-74. doi:10.7326/M16-2607
- 24 Kayani B, Konan S, Huq SS, et al. Robotic-arm assisted total knee arthroplasty has a learning curve of seven cases for integration into the surgical workflow but no learning curve effect for accuracy of implant positioning. *Knee Surg Sports Traumatol Arthrosc* 2019;27:1132-41. doi:10.1007/s00167-018-5138-5
- 25 Kayani B, Konan S, Pietrzak J, et al. The learning curve associated with robotic-arm assisted unicompartmental knee arthroplasty: a prospective cohort study. *Bone Joint J* 2018;100:1033-42.
- 26 Kurth T, Walker AM, Glynn RJ, et al. Results of multivariable logistic regression, propensity matching, propensity adjustment, and propensity-based weighting under conditions of nonuniform effect. *Am J Epidemiol* 2006;163:262-70. doi:10.1093/aje/kwj047
- 27 Alrajeb R, Zarti M, Shuia Z, et al. Robotic-assisted versus conventional total knee arthroplasty: a systematic review and meta-analysis of randomized controlled trials. *Eur J Orthop Surg Traumatol* 2024;34:1333-43. doi:10.1007/s00590-023-03798-2
- 28 Zhang F, Li H, Ba Z, et al. Robotic arm-assisted vs conventional unicompartmental knee arthroplasty: A meta-analysis of the effects on clinical outcomes. *Medicine (Baltimore)* 2019;98:e16968. doi:10.1097/MD.00000000000016968
- 29 Kirchner GJ, Stambough JB, Jimenez E, et al. Robotic-assisted TKA is Not Associated With Decreased Odds of Early Revision: An Analysis of the American Joint Replacement Registry. *Clin Orthop Relat Res* 2024;482:303-10. doi:10.1097/CORR.0000000000002783
- 30 Pius AK, Sporer SM, Sterling O, et al. Navigated and Robotic Total Knee Arthroplasty Do Not Confer Improved 5-Year Survivorship Compared to Conventional Total Knee Arthroplasty: An Analysis From the American Joint Replacement Registry. *J Arthroplasty* 2025;40:S130-9. doi:10.1016/j.arth.2025.03.047
- 31 Siddiqi A, Levine BR, Springer BD. Highlights of the 2021 American Joint Replacement Registry Annual Report. *Arthroplast Today* 2022;13:205-7. doi:10.1016/j.artd.2022.01.020
- 32 Bayliss LE, Culliford D, Monk AP, et al. The effect of patient age at intervention on risk of implant revision after total replacement of the hip or knee: a population-based cohort study. *Lancet* 2017;389:1424-30. doi:10.1016/S0140-6736(17)30059-4
- 33 Paxton EW, Inacio MCS, Khatod M, et al. Risk calculators predict failures of knee and hip arthroplasties: findings from a large health maintenance organization. *Clin Orthop Relat Res* 2015;473:3965-73. doi:10.1007/s11999-015-4506-4
- 34 Tay ML, Young SW, Frampton CM, et al. The lifetime revision risk of unicompartmental knee arthroplasty. *Bone Joint J* 2022;104:672-79.
- 35 Wall CJ, De Steiger RN, Vertullo CJ, et al. ASA class is a stronger predictor of early revision risk following primary total knee arthroplasty than BMI. *JBJS Open Access* 2025;10:e24.
- 36 Sezgin EA, W-Dahl A, Lidgren L, et al. Weight and height separated provide better understanding than BMI on the risk of revision after total knee arthroplasty: report of 107,228 primary total knee arthroplasties from the Swedish Knee Arthroplasty Register 2009-2017. *Acta Orthop* 2020;91:94-7. doi:10.1080/17453674.2019.1688006
- 37 Scanlon JP, McAuliffe MJ, Du P, et al. Obesity is associated with higher rates of revision following medial unicompartmental knee arthroplasty. *Knee* 2026;61:104419. doi:10.1016/j.knee.2026.104419
- 38 Vaotuuva D, O'Connor P, Belford M, et al. The Effect of Surgeon Volume on Revision for Periprosthetic Joint Infection: An Analysis of 602,919 Primary Total Knee Arthroplasties. *J Bone Joint Surg Am* 2023;105:1663-75. doi:10.2106/JBJS.22.01351
- 39 Lau RL, Perruccio AV, Gandhi R, et al. The role of surgeon volume on patient outcome in total knee arthroplasty: a systematic review of the literature. *BMC Musculoskelet Disord* 2012;13:250. doi:10.1186/1471-2474-13-250
- 40 Sutton PM, Murray JS. The National Joint Registry 22 years on: what have we learned about knee replacements? *Orthop Trauma* 2025;39:74-80. doi:10.1016/j.mporth.2024.12.008
- 41 Mohammad HR, Judge A, Murray DW. A Matched Comparison of the Long-Term Outcomes of Cemented and Cementless Total Knee Replacements: An Analysis from the National Joint Registry of England, Wales, Northern Ireland and the Isle of Man. *J Bone Joint Surg Am* 2021;103:2270-80. doi:10.2106/JBJS.21.00179
- 42 Mohammad HR, Matharu GS, Judge A, et al. Comparison of the 10-year outcomes of cemented and cementless unicompartmental knee replacements: data from the National Joint Registry for England, Wales, Northern Ireland and the Isle of Man. *Acta Orthop* 2020;91:76-81. doi:10.1080/17453674.2019.1680924
- 43 Miller LL, Prieto-Alhambra D, Trella-Larsen L, et al. Revision rates and postoperative mortality following total knee replacement in patients with rheumatoid compared to osteoarthritis: An analysis of data from the National Joint Registry for England, Wales and Northern Ireland. *Rheumatology* 2017;56(suppl_2) doi:10.1093/rheumatology/kex063.020
- 44 Bongartz T, Halligan CS, Osmon DR, et al. Incidence and risk factors of prosthetic joint infection after total hip or knee replacement in patients with rheumatoid arthritis. *Arthritis Rheum* 2008;59:1713-20. doi:10.1002/art.24060
- 45 Pai FY, Chang WL, Tsai SW, et al. Pharmacological thromboprophylaxis as a risk factor for early periprosthetic joint infection following primary total joint arthroplasty. *Sci Rep* 2022;12:10579. doi:10.1038/s41598-022-14749-y

Supplementary information: Tables S1-S9