

BMJ Open UK robotic arthroplasty clinical and cost effectiveness randomised controlled trial for hips (RACER-Hip): a study protocol

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ABSTRACT

Introduction The number of robotic-assisted hip replacement procedures has expanded globally with the intended aim of improving outcomes. Intraoperative robotic-arm systems add additional costs to total hip replacement (THR) surgery but may improve surgical precision and could contribute to diminished pain and improved function. Additionally, these systems may reduce the need for expensive revision surgery. Surgery with conventional instruments may be just as successful, quick and affordable. There is timely demand for a robust evaluation of this technology.

Methods and analysis The Robotic Arthroplasty Clinical and cost Effectiveness Randomised controlled trial for Hips (RACER-Hip) is a multicentre (minimum of six UK sites), participant–assessor blinded, randomised controlled trial. 378 participants with hip osteoarthritis requiring THR will be randomised (1:1) to receive robotic-assisted THR, or THR using conventional surgical instruments. The primary outcome is the Forgotten Joint Score at 12 months post-randomisation; a patient-reported outcome measure assessing participants' awareness of their joint when undertaking daily activities. Secondary outcomes will be collected post-operatively (pain, blood loss and opioid usage) and at 3, 6, 12, 24 months, then 5 and 10 years postrandomisation (including function, pain, health-related quality of life, reoperations and satisfaction). Allocation concealment will be accomplished using a computer-based randomisation procedure on the day of surgery. Blinding methods include the use of sham incisions for marker clusters and blinded operation notes. The primary analysis will adhere to the intention-to-treat principle. Results will adhere to Consolidated Standards of Reporting Trials statements.

Ethics and dissemination The trial was approved by an ethics committee (Solihull Research Ethics Committee, 30 June 2021, IRAS: 295831). Participants will provide informed consent before agreeing to participate. Results will be disseminated using peer-reviewed journal publications, presentations at international conferences and through the use of social media. We will develop plans to disseminate to patients and public with our patient partners.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- ⇒ Largest non-industry multicentre UK randomised controlled trial investigating patient-reported and clinical outcomes after robotic assisted total hip replacement.
- ⇒ Patients and outcome assessors blinded to surgical intervention through multiple methods including sham incisions and bespoke blinded operation notes.
- ⇒ Detailed assessment of acute and chronic patient-reported and clinical outcomes.
- ⇒ Cost-effectiveness evaluation using both within-trial and long-term modelling approaches.
- ⇒ No assessment of potential implementation considerations using a process evaluation framework.

Trial registration number ISRCTN13374625.

INTRODUCTION

Total hip replacement (THR) aims to relieve pain and disability resulting from osteoarthritis of the hip joint. While this can be a successful operation for most people, it can result in persisting pain or functional restrictions for some.^{1–4} One in 10 people report no measurable improvement in pain.¹ The causes of this are likely to be multifactorial. Surgeons are starting to use new technologies, such as intraoperative robotic-assisted systems to improve outcomes after THR.

Robotic systems may facilitate more precise and consistent intraoperative positioning of components (implant), which could reduce complications following THR. Most robotic systems use a combination of preoperative CT scanning and plain film radiographs (X-rays) to create an accurate three-dimensional model of the pelvis and hip joint. Imaging

is used to plan size and placement of the socket during surgery. Intraoperatively, small pins secure markers (arrays) allowing the robotic arm to accurately locate pelvic landmarks. The robotic arm reams the acetabulum with haptic restraint, which facilitates correct insertion of the acetabular implant.

More accurate component position may improve the biomechanical performance of the replaced hip. Subtle differences of component size and positioning can influence a range of motion or provoke tendonitis from rubbing against the edge of the component.^{5 6} Accurate restoration of leg-length and offset (the horizontal distance between the pelvis and the femur) are associated with improved functional outcomes and lower risk of chronic postsurgical pain.⁷⁻⁹ More accurate and consistent positioning may prevent chronic complications such as instability, fracture around components and loosening, which may reduce the need for revision surgery.¹⁰⁻¹²

Improvements in acute postsurgical pain may limit progression to chronic pain, shorten hospital stays and reduce National Health Service (NHS) costs.^{13 14} There could be other cost savings for healthcare systems. For example, 16% of successful clinical negligence claims following THR in the NHS are for leg-length discrepancy.¹⁵ It is unclear whether robotic assistance could improve postoperative outcomes to such a degree that their substantial costs would be offset by the savings.

There is potential for harm from robotic-assisted surgery, whether from longer operating times, pain or infection from placement of marker pins, radiation exposure from additional imaging or other unanticipated events which may occur.

Conventional THR often involves preoperative planning with plain film radiographs (X-rays), used to estimate implant placement. Surgeons are guided by intraoperative trialling to determine the final implant and position. This conventional technique has been in use for decades and is well understood by surgeons. Conventional approaches may be sufficiently accurate, resulting in outcomes that are similar or superior to robotic systems. Conventional THR surgery does not require drilling holes for marker (array) placement.

The use of robotic systems is increasing rapidly in the NHS and globally, with over 2000 systems worldwide (Personal communication, Edward Bird, Stryker, September 2023) The MAKO (Stryker, USA) system is the most frequently used robotic system in the NHS. However, robotic systems are expensive, costing approximately £1 million per robotic unit. There are additional operative costs for preoperative CT imaging, intraoperative single-use instruments and potentially longer time in theatre. If these systems are not cost-efficient, their use should be reconsidered.

Robotic surgery for THR: existing knowledge

A 2018 systematic review included seven studies: three randomised controlled trials (RCTs) (n=351) and four observational studies (n=1165).¹⁶ The RCTs tested a fully

autonomous system (different to the MAKO system) and found lower odds of intraoperative complications, including femoral fractures, during robotic compared with conventional THR (OR: 0.12, 95% CI: 0.05 to 0.34). There were no statistically significant differences in clinical outcomes between groups, including leg-length discrepancy (Standardised Mean Difference: -0.24, 95% CI: -0.61 to 0.12 measured radiologically).

A retrospective cohort study comparing MAKO (n=56) with standard surgery (n=51) found that the robotic-assisted system was associated with shorter hospital length of stay (mean (SD) 5.14 (1.98) days vs 8.11 (1.64) days, $p<0.001$).¹⁷ However, there were no differences in patient-reported outcome measures (PROMs) as measured by the Western Ontario and McMaster (WOMAC) Osteoarthritis Index and the Harris Hip Modified Score.

A cohort study (n=20) investigating surgical time showed robotic systems took on average 10 min longer than navigated THR.¹⁸ Another cohort study (n=15) assessed accuracy of preoperative templating for MAKO and found that it could predict the size of components used intraoperatively for the acetabular cup, femoral component and head diameter 100% of the time.¹⁹

Three cohort studies from the USA explored radiological outcomes of the MAKO system,²⁰⁻²² including placement of the acetabular components within a 'safe' zone.^{23 24} These zones were observed to have lower dislocation rates than conventional THR. All studies reported statistically significant improvements on the ability of the MAKO system to place the acetabular component in the safe zone.

Currently, no RCTs have evaluated the clinical and cost-effectiveness of the MAKO system for THR. A high-quality RCT with patient-centred clinical, and cost-effectiveness outcomes, is needed to establish whether robotic-assisted THR is superior for patients with hip osteoarthritis compared with conventional THR surgery.

Aim

The aim of the Robotic Arthroplasty Clinical and cost Effectiveness Randomised controlled trial for Hips (RACER-Hip) trial is to investigate whether robotic-assisted THR or conventional THR with conventional instruments is more clinically and cost-effective in a UK NHS setting on outcomes of hip function, pain, complications and quality of life for people with hip osteoarthritis.

Research question

What is the clinical and cost-effectiveness of performing THR with, or without, assistance from the MAKO robotic system on postoperative outcomes for people with hip osteoarthritis?

Objectives

Primary objectives

- To determine if robotic-assisted THR improves joint awareness at 12 months postrandomisation (measured

using the Forgotten Joint Score, FJS), compared with conventional THR surgery.

- ▶ To determine the cost-effectiveness of robotic-assisted THR in the UK NHS, compared with conventional THR.

Secondary objectives

- ▶ To compare pain intensity and opioid analgesic use over the first three postoperative days.
- ▶ To compare duration of surgery, blood loss, and time to hospital discharge.
- ▶ To compare function (FJS, Oxford Hip Score), health-related quality of life (HRQoL) (EQ-5D-5L), pain intensity, participant satisfaction, adverse events (AEs) and implant survival at 6 weeks (pain/HRQoL only), 3, 6 and 12 months and 2, 5 and 10 years postrandomisation.

METHODS AND ANALYSIS

Trial design

RACER-Hip is a multicentre, patient–assessor blinded, pragmatic, superiority RCT with embedded economic evaluation. A minimum number of six sites are expected to open to recruitment across England and Scotland. This is a phase III study according to the Ideas, Development, Exploration, Assessment, Long-term study (IDEAL) classification for evaluation of surgical interventions.² This paper and the study protocol were written following the Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT) guidelines for protocol reporting. **Figure 1** is the participant flow diagram, and a copy of the participant consent form is included as online supplemental file 1. A summary of core trial information is presented in the WHO trial registration data set in online supplemental file 2.

Outcome measures

Our choice of outcome measures was made in partnership with our patient and public involvement (PPI) group to ensure that selected measures were relevant and appropriate to patients. In line with SPIRIT guidance, **table 1** details the schedule of enrolment, interventions, and assessment.

Primary outcome

The primary clinical outcome is joint awareness measured using the FJS collected at 12 months postrandomisation. The FJS is a PROM with scores between 0 and 100, where 100 represents best possible outcome (ie, no awareness of joint). This scale was developed for joint replacement studies and has good evidence of validity, internal consistency and sensitivity to change.³ We selected the endpoint of 12 months to reflect the time it takes for recovery to plateau to a level typically maintained over the medium to long term.⁴

Secondary outcomes

The secondary outcomes are collected within two timeframes, short-term (acute) in-hospital outcomes,

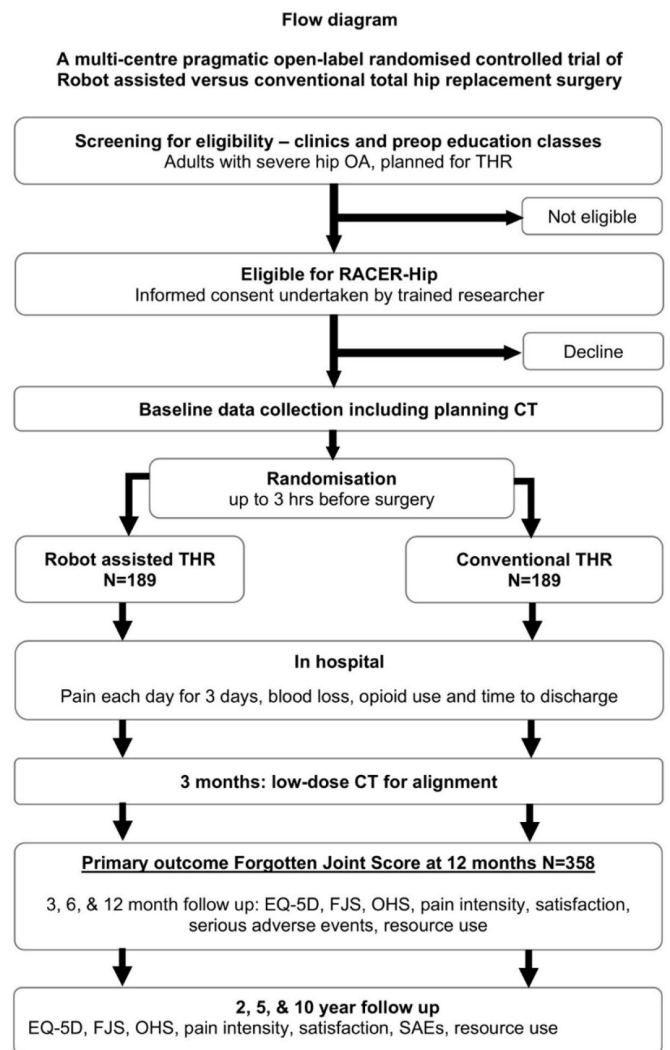


Figure 1 RACER-Hip participant flow diagram. EQ-5D, EuroQol five dimensions; FJS, Forgotten Joint Score; OA, osteoarthritis; OHS, Oxford Hip Score; RACER-Hip, Robotic Arthroplasty Clinical and cost Effectiveness Randomised controlled trial for Hips; SAEs, serious adverse events; THR, total hip replacement.

medium-term and long-term outcomes directly from participants from 6 weeks postrandomisation and beyond.

Acute postoperative (in-hospital) outcomes

All collected on day of surgery (day 0), or days 1–3 postoperatively.

- ▶ Duration of surgery (time from skin incision to application of final dressing).
- ▶ Estimated blood loss calculated using Brecher’s formula, based on preoperative and postoperative haematocrit measurements from routinely taken clinical blood measurements, and volume, if any, of blood transfused.²⁵
- ▶ Mean pain intensity, measured using an 11-point Numerical Rating Scale (NRS) for ‘pain right now’ and ‘average pain since yesterday’ on each morning of the first 3 days postoperatively.²⁶

Table 1 RACER-Hip SPIRIT outcomes and assessment schedule

Study period										
Enrolment		Baseline (pre-allocation)			Allocation Post-allocation					
Time point	$-t_2$	$-t_1$	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8
		Days	1,2,3	6 weeks	3 months	6 months	12 months	24 months	5 years	10 years
Enrolment										
Eligibility screen										
Informed consent	✓									
Randomisation	n=378	✓								
Interventions										
Robotic THR			n=189							
Conventional THR			n=189							
Assessments										
Primary outcome	FJS	✓								✓
Secondary outcomes	Pain intensity (NRS 11 point)	✓		✓	✓	✓	✓	✓	✓	✓
	Opioid usage		✓							
	Estimated blood loss		✓							
	Time to discharge		✓							
	Oxford Hip Score	✓			✓	✓	✓	✓	✓	✓
	EQ-5D-5L	✓		✓	✓	✓	✓	✓	✓	✓
	Post operative CT measures and process outcomes				✓					
	Resource use			✓						
	Participant satisfaction						✓			

EQ-5D-5L, EuroQol five dimensions; FJS, Forgotten Joint Score; NRS, Numerical Rating Scale; RACER-Hip, Robotic Arthroplasty Clinical and cost Effectiveness Randomised controlled trial for Hips; SPIRIT, Standard Protocol Items: Recommendations for Interventional Trials; t, time point; THR, total hip replacement.

- ▶ Total opioid use from the start of surgery to the end of day 3. Total morphine equivalent, using established conversion methods.²⁷
- ▶ Hours from surgery completion to hospital discharge.

Participant reported (out-of-hospital) outcomes

All collected at baseline (prerandomisation); 6 weeks (pain and HRQoL only), and 3, 6 and 12 months and 2, 5 and 10 years postrandomisation.

- ▶ Joint awareness using the FJS.³
- ▶ Overall hip pain and function using the Oxford Hip Score, a 12-item well-validated and widely used measure.²⁸
- ▶ Pain intensity right now and yesterday (0–11 NRS).
- ▶ HRQoL (EQ-5D-5L).²⁹
- ▶ Participant satisfaction with THR, measured using a five-point Likert scale.³⁰
- ▶ Implant survival assessed by reoperations relating to THR, and in addition to other reoperations, categorised using the National Joint Registry definition (not at baseline).³¹
- ▶ Resource use using participant questionnaires.
- ▶ Resource use linkage using NHS data sets (at 5 and 10 years).

Safety outcomes

- ▶ AEs related to the operation, anaesthetic or rehabilitation. Expected AEs (including serious) will be recorded as outcomes. Serious adverse events (SAEs) will be collected according to relevant Warwick Clinical Trials Unit (WCTU) Standard Operating Procedures (SOPs), from the day of randomisation for 90 days.

Process and fidelity outcomes

- ▶ Alignment measures at 3 months on a focused low-dose CT: rotation of femoral (version angle) and acetabular (version and abduction angle) components, leg-length and offset compared with the preoperative plan.
- ▶ Participant self-reporting of outpatient physiotherapy visits.

Eligibility criteria

Inclusion criteria

1. Osteoarthritis of the hip with pain, disability and radiological changes that in the opinion of the treating clinician, warrants THR.
2. Conservative therapy has been unsuccessful, as judged by the treating clinician.

Exclusion criteria

1. Osteoarthritis due to inflammatory arthropathy or intra-articular fracture, as judged by the treating clinician.
2. Revision surgery or need for complex implants, or any other implants than a standard hybrid construct (Trident I/II Exeter) or uncemented construct (Trident I/II Accolade), as determined by the treating clinician.

This includes nickel-free implants as well as those that require a long stem, augments, or custom-made devices.

3. Less than 18 years of age.
4. Unfit for THR, or surgery is otherwise contraindicated, for example, current infection.
5. Previous randomisation in the present trial, that is, contralateral hip.
6. Unable to take part or adhere to trial processes including prisoners or people unable to communicate or complete questionnaires in English, or people unable to give informed consent.

Participant identification

Potential participants will be identified by the attending clinical team in intermediate or secondary care clinics, from preoperative education classes, or from the surgical waiting list. Initial identification will be performed by clinical teams, if this is not a hip arthroplasty surgeon or a suitably trained member of clinical staff, a referral will be made to the appropriate clinic to assess eligibility. The ‘treating clinician’ is the person who sees the patient clinically at that time point and is suitably trained to make that decision.

Screening will be conducted using the electronic database directly by the site research teams. Potential participants will be screened and entered on the database. If suitable for inclusion, participants will be informed that they can discuss the study with a member of the research team if they wish to.

The local research team will be responsible for conducting the informed consent process before registering the participant and collecting baseline data. If a participant waits more than 6 months before surgery since completion of baseline data, data will be recollected prior to randomisation. Before surgery, all participants will have consent and eligibility reviewed.

Randomisation and treatment allocation

Participants will be allocated randomly to two treatment groups, in an equal ratio of 1:1. Randomisation will be based on a computer-based system held and controlled centrally by the WCTU programming team, independent of the RACER-Hip study team. A minimisation procedure will be used to determine allocation of treatment group, with a 70% random factor to ensure that treatment allocation is not predictable. The procedure will minimise for the following factors: age group (<60 compared with ≥60 years), hospital site, Body Mass Index (BMI) at baseline (<35, ≥35 kg/m²), planned implant construct (hybrid Trident Exeter or uncemented Trident Accolade) and previous contralateral hip replacement (yes/no).

Participants will be randomised after eligibility and consent has been confirmed. Randomisation will take place up to 3 hours prior to the planned start of surgery. This timing allows staff to arrange theatre for robotic surgery but not amend the order of the surgical list based on the outcome of the allocation. Local site arrangements



to indicate inclusion in the trial will be agreed in advance, to keep identification of included participants suitably concealed to avoid accidental unblinding.

There is a possibility that participants may become ineligible during the time between randomisation and the procedure commencing (such as a medical event prior to the operation). To maintain blinding in the small number of cases, this may happen if surgery can proceed within 72 hours of randomisation, then participants will receive their surgery as originally allocated. If the participant cannot receive treatment within 72 hours of planned start time, then the participant will be removed from the study and classified as 'became ineligible between randomisation and intervention'. These participants will not be used in the intention-to-treat (ITT) analysis and will be reported as a separate group in the final report and Consolidated Standards of Reporting Trials (CONSORT) chart. If the participant wishes to participate at a later date and is eligible, then they may be reregistered and receive a new treatment allocation.

Participants are free to withdraw from the whole trial, or from follow-up only, at any time with no effect on their standard of care. Prerandomisation and postrandomisation withdrawals will be monitored separately by the Trial Management Group (TMG) and oversight committees.

Trial interventions

The primary surgeon present during the procedure will be a consultant (attending) surgeon who has attained Certification of Completion of Training or be on the General Medical Council specialist register. They will be able to do both intervention and control procedures. In addition, they will have completed Stryker MAKO training course. If the primary surgeon plans to supervise another surgeon during any of the procedure, this must be declared on the randomisation form before the allocation is obtained, to prevent bias due to surgeon seniority.

All participants will undergo a CT scan to create a preoperative plan. This includes specific size of implants and placement. Surgeons will have access to this preoperative plan for both intervention and control group.

The implant constructs will be either Hybrid (Exeter cemented stem and Trident I/II uncemented socket) or uncemented construct (Accolade uncemented stem and Trident I/II uncemented socket). These represent the implants compatible with the MAKO robotic system and are also commonly used implants within the NHS.³²

All other care, including choice of anaesthetic and postoperative analgesia will be usual care.

Group 1: robotic total hip replacement (intervention)

The intervention will be use of the MAKO system to prepare the acetabulum and insert the acetabular component. The surgeon will have the option of using an express workflow which allows a CT plan of the femoral component position and a checkpoint verification of leg-length and offset. Alternatively, the surgeon can use the enhanced workflow which requires a tracker to be placed

in the femoral bone and provided information on the femoral version and centre of rotation of the femoral component as well as leg-length and offset.

Group 2: conventional total hip replacement (control)

The control group will receive a THR using conventional instruments with either hybrid or uncemented construct as detailed above.

Rehabilitation

A standardised physiotherapy programme for all participants across both arms of the trial has been developed and will be implemented at all sites. The provision of a self-directed physiotherapy programme is in accordance with the National Institute of Health and Care Excellence (NICE) recommendations, and all material developed for the study has been made in-line with the best current evidence and guidance and input from PPI members.³³ The self-directed programme includes personalised exercise prescription and gait re-education to begin on day of THR surgery, advice about recovery from THR on returning to activities and exercise.

Blinding

All study participants and assessors will be blinded to treatment allocation throughout the study. Research staff who collect participant outcomes will be considered assessors, and be trained in the importance of maintaining blinding.

Site staff will be asked to not reveal treatment allocations. Drapes and headphones will be used in theatre to maintain blinding where needed, which is a common surgical practice to preserve sterility. Sham incisions of approximately 1 cm will be used in the control group to maintain participant blinding.

Blinding in surgical trials using sham incisions is strongly recommended by the Royal College of Surgeons.³⁴ A customisable operation note, based on previous experience in other WCTU trials, has been designed to ensure that intraoperative data collection is not a weak point in maintaining blinding.^{35 36}

All participants will have standardised operation notes containing no details regarding the robotic system, and details on usage will be recorded by surgeons in an online form linked directly to the secure trial database. Information on MAKO consumables utilised will be placed in a sealed envelope and entered into patient notes.

Unblinding is anticipated to be a rare event and should only happen when knowledge of treatment allocation is needed for emergency clinical management. We do not anticipate that knowledge of the treatment allocation will influence any urgent clinical management in this setting, hence no formal unblinding process will be developed. If unblinding is required for any reason, the trial team are to be contacted directly.

End of trial

The trial will end when the final follow-up data have been received and entered, and no additional follow-up

activities are planned. The trial will only be stopped prior to this if mandated by the Research Ethics Committee (REC), the Medicines and Healthcare products Regulatory Agency (MHRA), the Trial Steering Committee (TSC) or if funding for the trial ceases. The REC will be notified within 90 days of trial closure.

Patient and public involvement

A patient advisory group of 10 participants was formed to help develop the application and study design, where they aided in the selection and hierarchy of outcomes measures. They reviewed patient-facing documents and gave additional feedback on trial blinding and communicating risk associated with additional radiation. Two of the group became coapplicants and PPI representatives at monthly TMG meetings. Another PPI representative sits on the oversight TSC. PPI representatives are supported by the trial lead co-applicant for PPI.

Safety reporting, AE and SAEs

All AEs, SAEs, serious adverse device events (SADEs) and unanticipated SADEs will be defined using standard criteria. For this study, AEs will be recorded for events that occur during the inpatient stay and up to 12 months postrandomisation and are thought to be related to the trial interventions or the condition under study. This may include any events related to anaesthetic, physiotherapy or other trial processes. A list of expected AEs will be produced and be treated as outcomes and reported as such.

Information on AEs and SAEs occurring from the date of randomisation up until 12 months postrandomisation will be collected. The cosponsors will be notified within 24 hours of the research staff becoming aware of the event. All events will be followed up until the event has been resolved and an outcome has been agreed.

Statistical analysis

Sample size

The primary outcome measure used in the sample size calculation is the FJS. In this trial, a between-group difference of 12 points was chosen as a target difference, with the assumed SD for THR is 32 resulting in a moderate effect size of 0.38.³⁷ Based on a statistical power of 90% and a two-sided type I error of 5%, the required total sample size is 302 participants. After an adjustment to account for 20% loss to follow-up, the sample size is 378 participants. No surgeon clustering is expected, given this is an equipoise study with surgeons performing both interventions.

Statistical analysis plan

Final trial analysis will be conducted in line with the CONSORT guidelines.³⁸ A detailed statistical analysis plan (SAP) will be developed by trial statisticians and reviewed by appropriate oversight committees prior to the final analysis. Descriptive data will be summarised using appropriate statistical methods (eg, means and SDs for continuous data)

The primary analysis model will investigate the difference in the FJS at 12 months postrandomisation between the treatment groups under an ITT principle. The primary analysis model will be a generalised linear model with terms for allocation group, age group (<60, ≥60 years) recruiting site, gender, BMI group (<35, ≥35 kg/m²), planned implant type (hybrid Trident Exeter or uncemented Trident Accolade) and previous contralateral hip replacement. Fixed and random-effect models, with potential random effects of surgeon and site will be investigated. Sensitivity analyses will be used to explore modelling assumptions and the impact of treatment non-compliance.

The frequency and pattern of missing data in outcome data will be scrutinised and reasons recorded where possible. Multiple imputation will be used, with imputed data sets reported secondary to primary analysis models.

Prespecified subgroup analyses will be used to explore whether the intervention effect differs within subgroups. Each model will repeat the primary analysis model with an additional interaction term included in the model between treatment group and the factor of interest. The subgroups under investigation will be BMI group (<35, ≥35 kg/m²) and planned implant type (hybrid Trident Exeter or uncemented Trident Accolade). Results of these models will be deemed exploratory and subsidiary to the primary analysis results.

Database

A customised database system has been developed by the experienced programming team at WCTU, with an associated detailed data management plan produced in accordance with WCTU SOPs to ensure the collection of high-quality data over the duration of the trial.

Health economic analysis

A within-trial economic evaluation will be conducted according to the ITT principle. The base case analysis will take a UK NHS and personal social services perspective, according to the recommendations of the NICE reference case.³⁹

Participants' health and care resource use, made in connection with their THR, will be collected at all follow-up time points. Time lost from work due to THR will also be recorded. Differences in index surgical procedures will be explored through changes in use of surgical time and facilities. Healthcare resource use will be costed using most recently available published national reference costs, reflatd to a common year.⁴⁰

HRQoL will be assessed using the EQ-5D-5L questionnaire. Scores will be converted to health status scores using the UK value set recommended by NICE guidance at the time of analysis. Using the trapezoidal rule, the area-under-the-curve of health status scores will be calculated, providing patient-level Quality Adjusted Life Years (QALY) estimates.

Mechanisms of missingness of data will be explored and multiple imputation methods will be applied to

impute missing data. Imputation sets will be used in bivariate analysis of costs and QALYs to generate within-trial (12 month) incremental cost per QALY estimates and CIs.^{41–43} Findings will be analysed and visualised in the cost-effectiveness plane, as cost-effectiveness acceptability curves, net monetary benefit and value of information analysis.

A limitation of trial-based economic analyses of emergent technologies is that they may not accurately represent real costs of use. Use is typically through a monthly hire cost, with cost per procedure dependent on hospital throughput. The costs of technologies change in response to market conditions. Sensitivity analysis will explore these issues. Analysis will be limited to within-trial data if differences in costs and outcomes are convergent or if either surgical path is robustly dominant in the first 12 months. If not, then longer term models will be constructed using longer term follow-up data and other sources.

Where differences in cost and outcomes are convergent within the trial follow-up period, cost-effectiveness will be affected if there are differences in the long-term risk of revision surgery. If so, a decision model will be constructed using longer term trial follow-up data.

Ethics and dissemination

The trial has full ethical approval from the West Midlands—Solihull Ethical Review Board (NRES 21/WM/0143 30 June 2021). The trial will adhere to the Declaration of Helsinki and Good Clinical Practice and follow all appropriate WCTU SOPs. Participants will provide informed consent before agreeing to participate. An independent Data Monitoring Committee and Trial Steering Committee (TSC) will provide an oversight from set up to the closure of the trial. Both committees will include independent members under the definition provided by NIHR and WCTU SOPs, and separate charters for each committee will be developed. Data monitoring plans will be implemented by the trial cosponsors. Amendments to the protocol will be communicated to sites by the trial co-ordinating team.

Data sharing

Any data sets generated will be available on request from WCTU Data Sharing Committee (DSC) (WCTUDataAccess@warwick.ac.uk). Deidentified data will be available for non-commercial use, up to a year after the publication of the trial results, or from metadata stored in a university repository for up to 10 years without investigator support. To access trial data, third parties must complete a data-sharing agreement, have an ethically approved protocol in place and agree to the approved protocol with the WCTU DSC. Data may be used for commercial purposes, according to the conditions above, but will need additional agreements in place, which may include a license fee. Available data will include (but is not exclusive to) deidentified individual participant data, the study protocol, SAP, informed consent sheets and analytic codes.

Trial registration and study timelines

The trial is registered with the ISRCTN register (ISRCTN13374625). The current version of the protocol is V3.0, approved on 12 July 2023. The planned dates of the study are from 1 July 2021 to 31 December 2024, with long-term follow-up planned for up to 10 years to 2033.

Dissemination and publication

The results of the study will be reported first to trial collaborators at a TMG meeting, with the main study report being drafted by the trial team and agreed by the TSC before submission for publication. Final results of the trial will be reported in accordance with CONSORT guidelines.³⁸ The final results publication will be submitted to a major peer-reviewed journal. Results will be presented at international meetings, such as the British Orthopaedic Association. Dissemination to patients and the public will be led in conjunction with our patient partners, who have been closely involved throughout the study development. Dissemination to trial participants will follow current Health Research Authority (HRA) guidelines, with summaries provided on the trial website and social media.

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Contributors PDHW and ETD are co-chief investigators and the main grant holders for this project and are responsible for identifying the clinical question. ETD, HP, JB, DRE, FH, CEH, JM, AM, TS, JAS, SR, MU and PDHW are coapplicant grant holders and are responsible for the design and conduct of the RACER Hip study. These authors contributed to the development of the main study protocol, the draft of the manuscript and approval of the final version. JS and JW are patient representatives as well as coapplicants on the grant and gave expertise from their perspectives throughout the study. JG, ETD, HP, SS, HB, JB, DRE, CEH, FH, JM, HN, AM, TS, JAS, SR, MU, CK and PDHW contributed to the development of the main trial protocol, in addition to contributing to the writing of the manuscript and approval of the final version. JG led the first draft of the manuscript, submitted this manuscript, and acted as corresponding author. This paper and the study protocol were written following the Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT) guidelines for protocol development. A SPIRIT checklist was included as a supporting document during the submission process.

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Competing interests Stryker is providing funding for consumables, surgical instruments, preoperative CT costs, 15 min of theatre time and the provision of robotic systems at two of the recruitment sites, according to contractual arrangements which align fully with the National Institute for Health Research (NIHR) contracts. Appropriate contracts are in place to ensure the independence of the trial team with regard to study design, data collection, management, analysis and interpretation in-line with NIHR reporting standards. MU has been a chief investigator and is current, or past, coinvestigator on multiple previous

and current research grants from the UK NIHR, and is a coinvestigator on grants funded by the Australian NHMRC and Norwegian MRC. He was an NIHR Senior Investigator until March 2021. He is a director and shareholder of Clinvivo that provides electronic data collection for health services research. He is part of an academic partnership with Serco, funded by the European Social Fund, related to return to work initiatives. He receives some salary support from University Hospitals Coventry and Warwickshire. He is a coinvestigator on two current and one completed NIHR-funded studies that have, or have had, additional support from Stryker. DRE, HP, JB and JG are supported from NIHR Research Capability Funding via University Hospitals Coventry and Warwickshire. JB and TS have been and is currently coapplicant on multiple previous and current research grants from the UK NIHR. JB has had travel expenses reimbursed by societies/organisations for invited contributions. TS has acted as Associate Editor for clinical journals and as a Committee member on the UK NICE Technology Committee. FH has held multiple research study grants with Stryker. In addition, he has held research grants from Smith & Nephew, Corin, IOC, NIHR. FH has royalties with Smith & Nephew, Stryker, Corin and MatOrtho. FH has received consulting fees from Stryker. FH has received support for attending meetings and/or travel from Stryker, Smith & Nephew, AO Recon, Bone and Joint Journal. FSH is a member of the *Bone and Joint Journal Editorial Board*, a trustee of the British Orthopaedic Association and a member of the BOSTAA Executive Committee. All other authors declared no additional competing interests.

Patient and public involvement Patients and/or the public were involved in the design, or conduct, or reporting or dissemination plans of this research. Refer to the Methods section for further details.

Patient consent for publication Not required.

Provenance and peer review Not commissioned; peer reviewed for ethical and funding approval prior to submission.

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Supplementary File 1: RACER-Hip Consent Form V2.0_17Mar2022

**Robotic Arthroplasty: a Clinical and cost Effectiveness Randomised controlled trial for Hips
(RACER-Hip) - Consent Form**

Chief Investigators: Mr Peter Wall/Professor Edward Davis

Name of Site: <<Site Name>> Local PI: <<XXXX>>

Participant ID

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Please read each statement and initial the box if agreed

Initials

1. I confirm that I have read and understood the information sheet (Version..... Date.....) for the above trial. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected.

3. I understand that relevant sections of any of my medical notes and data collected during the trial may be looked at by responsible individuals from the University of Warwick, from regulatory authorities, or from the NHS Trust, where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.

4. I understand that appropriate personal identifying information will be collected, stored, and used by the research team to perform this trial to enable the trial teams to contact me to follow up of my health status. This is on the understanding that any information will be treated with the strictest security and confidentiality.

5. I understand that the information held and maintained by NHS Digital and other Central UK NHS bodies may be used to provide information about my health status. This will involve us linking your data (including personally identifiable data) with routine NHS datasets such as the National Joint Registry, Scottish Arthroplasty Project and NHS Digital.

6. I understand that in order to plan my surgery, CT scan images will be sent outside the United Kingdom to the company that supplies the robot (Stryker, USA). I understand that these images will contain at least two identifiers (e.g., name, hospital number or date of birth) but these will only be seen by employees of Stryker and will not be shared with any other party.

7. I understand that the information collected about me will be used to support other research in the future, and this anonymised data will be stored in a data repository so it may be shared with other researchers for future research, development, and learning.

8. I agree to being contacted to remind me that a questionnaire is due, to request further information, to help complete a questionnaire or to receive trial results, based on the contact information I provide.

9. I agree to my GP being informed of my participation in the study.

Yes No

OPTIONAL DATA SHARING: I consent to my health data being collected during the RACER study to be shared with Stryker Orthopaedics (please tick one option)

Yes No

Patient Name:

Signature:

Date:

Person taking consent (and role):

Signature:

Date:

For witnessed verbal consent: I witnessed accurate reading of the consent form to the patient, who could ask any questions and was happy with the responses.

Person who witnessed consent (and role):

Signature:

Date:

Supplementary File 2: RACER-Hip WHO trial registration data set

Data Category	Information
<i>Primary Registry and Trial Identifying Number</i>	ISRCTN13374625
<i>Date of Registration in Primary Registry</i>	07/05/2021
<i>Secondary Identifying Numbers</i>	NIHR HTA – 131407, IRAS 295831
<i>Source(s) of Monetary or Material Support</i>	National Institute for Health Research, Health Technology Assessment
<i>Primary Sponsor</i>	University Hospitals Coventry and Warwickshire
<i>Secondary Sponsor(s)</i>	University of Warwick
<i>Contact for Public Queries</i>	racer-hip@warwick.ac.uk
<i>Contact for Scientific Queries</i>	Mr Peter Wall (co-Cl), Royal Orthopaedic Hospital, Birmingham, UK
<i>Public Title</i>	Can robotic systems improve outcomes for people having a hip replacement?
<i>Scientific Title</i>	Robotic Arthroplasty: a Clinical and cost-Effectiveness Randomised controlled trial for Hips (RACER-Hip)
<i>Countries of Recruitment</i>	UK
<i>Health Condition(s) or Problem(s) Studied</i>	People with osteoarthritis undergoing total hip replacement
<i>Intervention(s)</i>	Intervention: Robotic assisted THR, with preoperative CT imaging. Control: Conventional THR surgery, with preoperative CT imaging.
<i>Key Inclusion and Exclusion Criteria</i>	<p><i>Inclusion criteria</i></p> <ul style="list-style-type: none"> i. Osteoarthritis of the hip with pain, disability and radiological changes warrants THR. ii. Conservative therapy has been unsuccessful, as judged by the treating clinician. <p><i>Exclusion criteria:</i></p> <ul style="list-style-type: none"> i. Osteoarthritis due to inflammatory arthropathy or intra-articular fracture. ii. Revision surgery or need for complex implants. iii. Age < 18 years iv. Unfit for THR, or surgery is otherwise contra-indicated, for example, current infection v. Previous randomisation in the present trial, i.e. the other hip vi. Unable to take part or adhere to trial processes <p>(Full details given in main text)</p>
<i>Study Type</i>	Interventional Allocation: randomised; individual assignment Phase III
<i>Date of First Enrollment</i>	March 2022

Data Category	Information
<i>Sample Size</i>	378
<i>Recruitment Status</i>	Recruiting at time of submission
<i>Primary Outcome(s)</i>	“Joint awareness” measured using the Forgotten Joint Score (FJS) at 12 months post-randomisation
<i>Key Secondary Outcomes</i>	In hospital (days 1,2,3): Intra-operative blood loss, operative time, pain, time to discharges and total opioid usage. Out of hospital (Six weeks, three, six and 12 months and two, five and 10 years):Oxford Hip Score, pain (intensity), health related quality of life, surgery related adverse events, patient satisfaction, implant survival.
<i>Ethics Review</i>	West Midlands Solihull, 30/06/2021