

ACCEPTED MANUSCRIPT • OPEN ACCESS

Pre-clinical evaluation of a smartphone-assisted navigation system for surgical pin positioning in total knee arthroplasty

To cite this article before publication: David Bull *et al* 2026 *Med. Eng. Phys.* in press <https://doi.org/10.1088/1873-4030/aeb26c>

Manuscript version: Accepted Manuscript

Accepted Manuscript is "the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an 'Accepted Manuscript' watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors"

This Accepted Manuscript is © 2026 The Author(s). Published on behalf of Institute of Physics and Engineering in Medicine by IOP Publishing Ltd..



As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 4.0 licence, this Accepted Manuscript is available for reuse under a CC BY 4.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence <https://creativecommons.org/licenses/by/4.0>

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the [article online](#) for updates and enhancements.

Journal Title

Paper

Pre-clinical evaluation of a smartphone-assisted navigation system for surgical pin positioning in total knee arthroplasty

David Bull¹, Jiaxin Zhang^{2,*}, Shuqiao Xie³, Pierluigi Cuomo², Gareth G. Jones², Yuqi Chen² and Anthony M. J. Bull²

¹ Department of Trauma & Orthopaedics, The Hillingdon Hospitals NHS Foundation Trust, Hillingdon Hospital, Uxbridge UB8 3NN, United Kingdom
² Department of Bioengineering, Imperial College London, Sir Michael Uren Hub, White City Campus, London W12 0BZ, United Kingdom
³ Smart Surgical Solution Ltd., Barnet, London EN4 9EB, United Kingdom

*Author to whom any correspondence should be addressed.

E-mail: j.zhang23@imperial.ac.uk

Keywords: surgical navigation, total knee arthroplasty, smartphone-based system, alignment, navigation system

Abstract

Total knee arthroplasty (TKA) success is highly dependent on accurate implant alignment, however, 80% of procedures globally are performed manually. Manual procedures have higher alignment errors compared to robotic platforms and patient-specific instrumentation, yet these have limitations of high cost and intraoperative inflexibility, respectively. This study aimed to evaluate the intraoperative pin positioning accuracy and flexibility of a smartphone-assisted navigation system using CT-derived surgical plans. Three participants used the navigation system to perform 108 guide pin insertions (54 femoral, 54 tibial) on surrogate bone models based on CT-derived surgical plans. Testing included both default mechanical axis targets (0°) and user-selected navigated targets ranging from -3° to 3°. Accuracy was assessed by comparing achieved pin trajectories with the preoperative surgical plan. Median absolute angular deviations achieved ranged from 0.9° to 1.6° across all component-plane combinations, with an overall median deviation of 1.3° (IQR 0.6–2.1°). The proportion of insertions within a predefined ±3° clinical accuracy threshold ranged from 83.3% to 100%, and all component-plane combinations demonstrated deviations significantly within this threshold ($p < 0.00001$). These findings support the technical feasibility of the smartphone-assisted navigation system for surgical pin positioning under controlled pre-clinical conditions. Further studies will evaluate the navigation system in cadaveric models with experienced orthopaedic surgeon participants.

1. Introduction

Total knee arthroplasty (TKA) is regarded as one of the most cost-effective and successful operative procedures[1]. However, there are reports that a significant number of patients experience dissatisfaction postoperatively due a multitude of reasons[2], including persistent pain and functional limitation[3]. Malalignment is a key cause of this and is directly linked to instability, pain, and range of motion limitations[4–6]. Small deviations in implant alignment can increase the wear of components, distribute the patient’s weight unevenly, and increases the risk of postoperative complications, such as loosening, instability, and potentially the requirement for revision surgery. Therefore, optimal implant alignment is critical for improving patient reported outcomes in TKA. Achieving alignment depends on accurate placement of the surgical cutting jig, which defines the resection planes on the femur and tibia[7].

Despite assistive technologies being developed, such as computer-assisted surgery (CAS), robotic platforms, and patient-specific instruments (PSI), 80% of TKA is still performed

manually[8], this often leads to greater errors in alignment when compared to those that use assistive technologies[9]. A major reason for CAS and robotic platforms not being adopted more rapidly is due to higher cost and logistical overhead[10]. PSI, whilst not being as comparatively expensive, offers no flexibility intraoperatively[11], and often takes considerable time for the customised part to be made.

A surgical navigation system has been developed to address these limitations of accuracy and intraoperative flexibility. The system utilises computerised-tomography (CT) scans of the patient's knee to create a surgical navigation plan using a machine-learning approach. The surgical plan is loaded onto an application on a dedicated smartphone which is attached to a handpiece. The application navigates the surgeon to achieve the surgical plan of surgical pin positioning for a standard cutting jig. The surgeon is able to adjust this plan intraoperatively in real time.

In this study, a prototype of the surgical navigation system was evaluated on surrogate bone models. The primary aim of this study was to determine the guided pin positioning accuracy achievable using the navigation system under controlled pre-clinical conditions.

2. Methods

2.1. Navigation System Workflow and Instrumentation

The smartphone-assisted navigation system comprises three main functional units, the: cloud-based surgical planning platform, smartphone application, and physical navigation handpiece. These components operate through two sequential stages, preoperative planning and intraoperative navigation, with the workflow summarised in Figure 1. The preoperative stage generates a patient-specific navigation model from CT-derived anatomy and surgical planning, while the intraoperative stage uses this model through the smartphone application together with the physical navigation handpiece to guide surgical pin fixation.

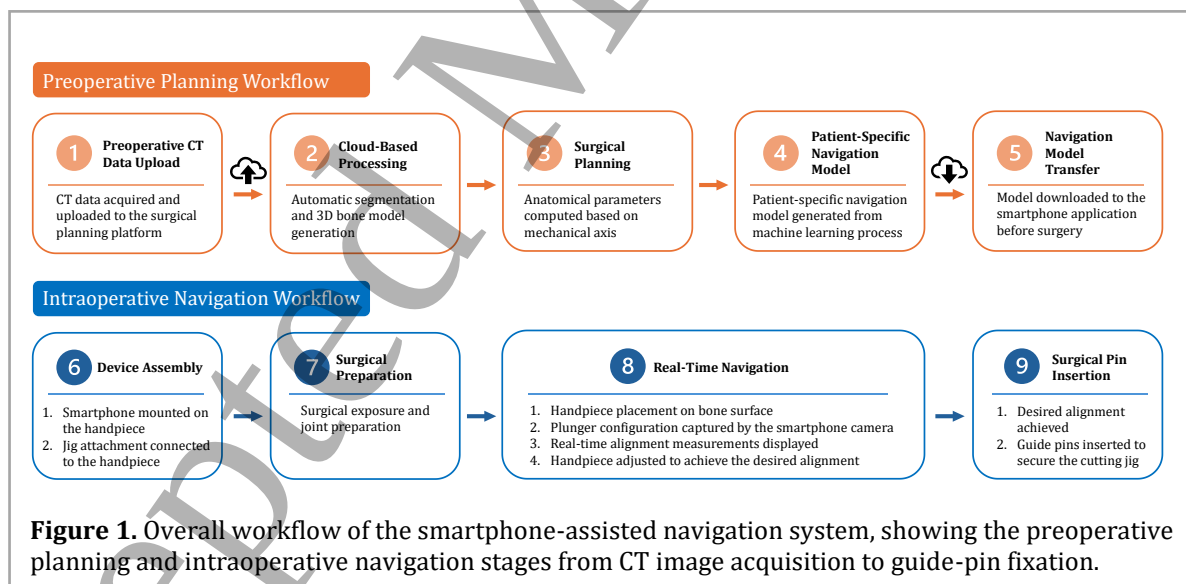


Figure 1. Overall workflow of the smartphone-assisted navigation system, showing the preoperative planning and intraoperative navigation stages from CT image acquisition to guide-pin fixation.

During the preoperative planning workflow (Figure 1, steps 1–5), preoperative CT data are acquired and uploaded to a secure, cloud-based surgical planning platform. The images are automatically segmented to generate three-dimensional (3D) geometric models of the relevant bony anatomy. Based on these models, key anatomical parameters, including the mechanical axes, are computed and used to define the surgical plan. A patient-specific machine-learning navigation model is then generated from the CT-derived bone geometry and downloaded to the smartphone application before surgery, with the model generation and registration process detailed below.

Intraoperatively (Figure 1, steps 6–9), the smartphone containing the patient-specific navigation model is mounted on the navigation handpiece and the appropriate femoral or tibial cutting-jig attachment is connected, ordered according to surgical preference. Following surgical exposure and preparation of the relevant bone surface, the handpiece and phone construct is placed directly on the distal femur or proximal tibia. The plungers of the handpiece conform to the local bone-surface topography, and the resulting plunger configuration is captured by the smartphone camera. This plunger configuration is used by the application in real-time to display the position of the cutting guide in terms of implant condylar resection height, flexion–extension, and varus–valgus alignment. The surgeon can then adjust the device to achieve the surgical plan; intraoperative adjustment as a quantified deviation from the plan can be effected. Once the desired parameters are achieved, surgical pins are inserted through the standard pin holes of the cutting jig to secure the jig to the bone.

The principal physical components used during intraoperative navigation are shown in Figure 2. The navigation handpiece is a lightweight, single-use plastic device designed to securely mount a smartphone (Figure 2A) and incorporates an array of mechanical plungers on its bone-facing surface (Figure 2B). When positioned on the bone, the plungers conform to the local surface topography (Figure 2C). The handpiece connects to the cutting jig through a dedicated metal attachment, with separate attachments provided for the femoral and tibial jigs (Figure 2D).

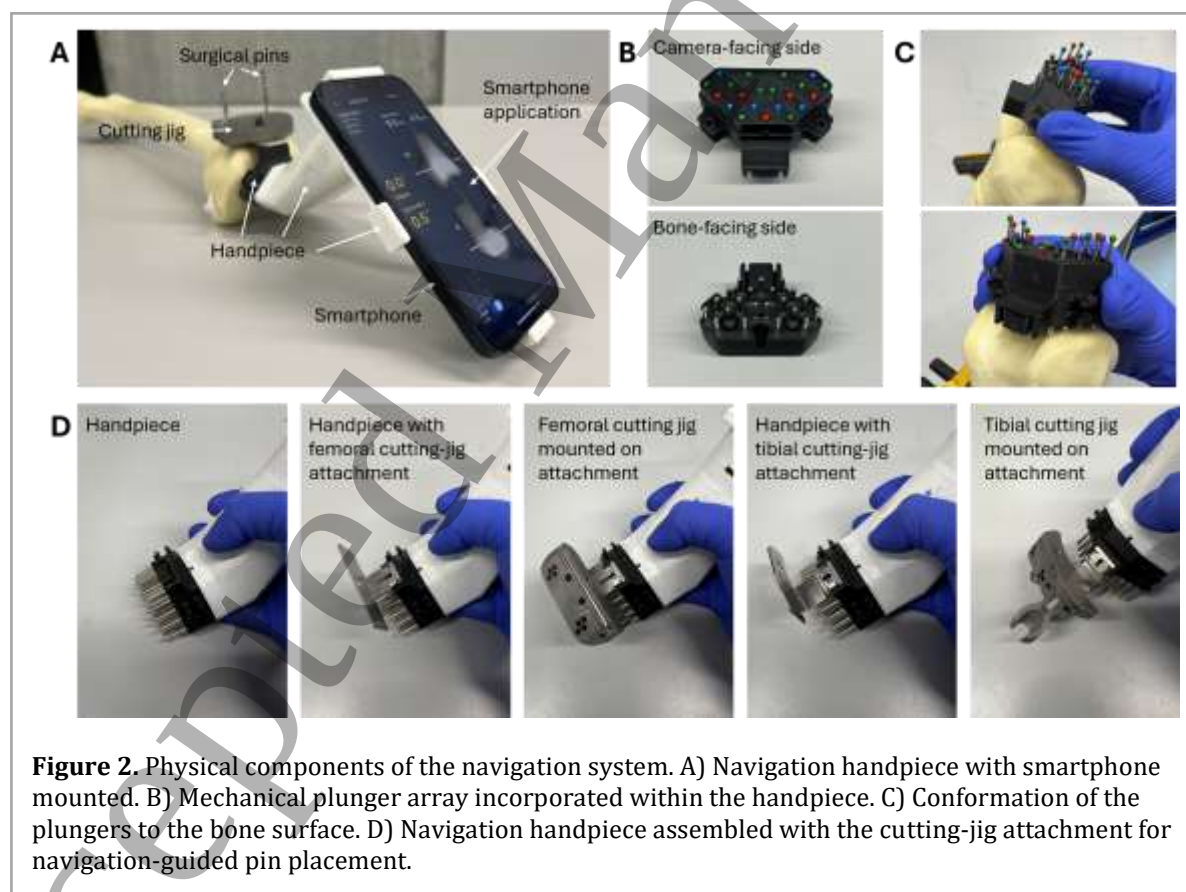


Figure 2. Physical components of the navigation system. A) Navigation handpiece with smartphone mounted. B) Mechanical plunger array incorporated within the handpiece. C) Conformation of the plungers to the bone surface. D) Navigation handpiece assembled with the cutting-jig attachment for navigation-guided pin placement.

2.2. Patient-specific Navigation Model and Intraoperative Registration

A patient-specific navigation model was generated from the segmented 3D geometry of the femur and tibia. During model generation, a virtual representation of the navigation handpiece is positioned at multiple locations and orientations across the distal femoral and proximal tibial surfaces. At each position, the extension of the individual plungers is quantified together with the corresponding position and orientation of the handpiece relative to the predefined bone

axes. This process generates more than 100,000 spatial and measurement relationships for each patient-specific model. These paired data are used to train a patient-specific machine-learning model relating the plunger configuration to the spatial position and orientation of the navigation device.

Intraoperative registration of the physical handpiece to the preoperative CT-derived anatomy is then achieved through this patient-specific model. During intraoperative use, the measured plunger configuration is matched through the patient-specific model to estimate the handpiece pose relative to the predefined bone axes. The corresponding navigation parameters, including varus/valgus and flexion/extension alignment, are then displayed in real time on the smartphone application, allowing the user to adjust the handpiece to the desired target before guide-pin insertion.

2.3. Participants and Test Samples

Three participants were recruited for this study, which was designed as a controlled technical validation of the navigation platform. All participants were biomechanical engineers with prior training and experience using the navigation system to minimise variability associated with early device familiarisation. Testing was conducted using three surrogate bone geometries fabricated in-house using polyurethane foam (Polycraft Rigid 145, MBFibreglass). Each geometry was generated from an independent cadaveric CT dataset, and each test sample consisted of a paired femoral and tibial surrogate model representing the anatomy of a separate donor. The CT-derived anatomical geometries used in this study were generated from cadaveric imaging data obtained under institutional tissue bank governance and research ethics approval.

2.4. Experimental Protocol and Pin Insertion

Each participant was required to perform surgical pin insertion on all three surrogate bone geometries with the objective of achieving neutral alignment ("zero" position) defined as zero varus/valgus and zero flexion/extension according to the surgical plan. For each femur tibia pair, three replicates were tested and each participant repeated the procedure three times.

In addition, because the navigation system allows surgeons to select alignment targets based on either condylar resection height or angular parameters (flexion/extension and varus/valgus), participants were also instructed to perform pin insertion using self-selected alignment targets. For these trials, participants selected target flexion/extension and varus/valgus angles within a range of -3° to $+3^{\circ}$ before navigation. The selected targets were visible to the participants during navigation. Angular deviation was calculated as the difference between the achieved pin position and the corresponding target angle. Three such tests were conducted per participant.

2.5. Post-Insertion Measurement and Data Collection

The surrogates were mounted and secured on a custom measurement jig incorporating reference lines corresponding to the preoperative surgical plan (Figure 3). For each surrogate, the metal surgical pins were removed and replaced with two coloured replacement pins (one blue, one green) of identical size (3.2mm standard diameter) to facilitate image-based detection. A fixed camera was positioned centrally relative to the measurement jig and used to acquire images in the coronal and sagittal planes (Figure 3A and B).

Camera positioning and imaging geometry were standardised to minimise distortion-related measurement error. Pin orientation was determined automatically using an in-house computer-vision algorithm. The algorithm automatically detected the pin trajectory and converted the image-based measurements to angular values relative to the corresponding

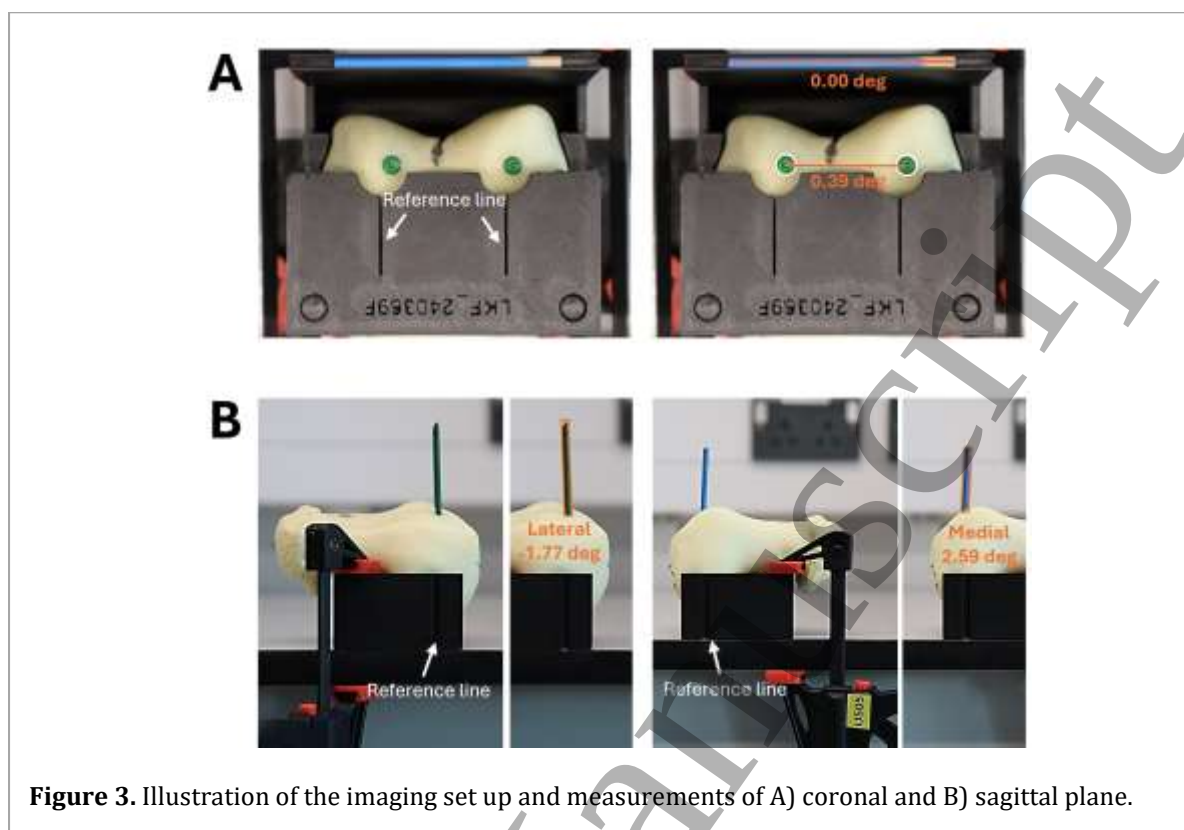


Figure 3. Illustration of the imaging set up and measurements of A) coronal and B) sagittal plane.

reference lines. The automated measurement method was validated prior to the study to confirm its accuracy and repeatability for angular measurement.

2.6. Statistical Analysis

The primary outcome was the clinical success rate, defined as the percentage of guide pin insertions falling within the clinically acceptable variation of $\pm 3^\circ$ [12]. Data were found to be non-normally distributed. A two-tailed, one-sample Wilcoxon Signed-Rank test was used on the pooled real angular deviation for each plane to determine whether the median angular deviation lay within the clinically acceptable margin of $\pm 3^\circ$. In addition, differences in absolute angular deviation between paired default and user-selected target conditions were assessed using the Wilcoxon signed-rank test, while differences in clinical success rates between the paired target conditions were assessed using McNemar's test. Clinical success rates are reported as proportions with corresponding 95% confidence intervals. For all analyses, a p -value of <0.05 was considered statistically significant.

3. Results

A total of 108 guide pin insertions were performed (54 femoral and 54 tibial) across the study and included in the final analysis. Measurements were obtained for both femoral and tibial

Table 1. Overall Performance and Accuracy of the Navigation System for Femoral and Tibial Guide Pin Insertions.

Component	Anatomical Plane	Median Absolute Angular Deviation, ° (IQR)	Range of Angular Deviation, °	Clinical Success Rate, % (95% CI)
Femur (n=54)	F/E	1.6 (0.8 to 2.5)	-7.9 to +2.1	83.3 (71.3–91.0)
	V/V	1.3 (0.7 to 2.1)	-3.9 to +1.0	85.2 (73.4–92.3)
Tibia (n=54)	F/E	1.4 (0.9 to 2.6)	-5.3 to +4.4	92.6 (82.4–97.1)
	V/V	0.9 (0.3 to 1.5)	-2.3 to +2.7	100 (93.4–100)
Overall				90.3 (85.6–93.6)

^aData are presented as the Median Absolute Angular Deviation with interquartile range (IQR) in degrees, calculated across all 54 insertions for each component. The Range of Deviation indicates the minimum and maximum angular deviation (error) observed in the set of 54 real-value measurements for each component/plane combination. V/V = Varus(+)/Valgus(-); F/E = Flexion(+)/Extension(-). Success Rate represents the percentage of insertions achieving an absolute angular deviation of $\leq 3^\circ$ with 95% confidence intervals calculated for the corresponding proportions.

components in the varus/valgus and flexion/extension planes, under default (“zero”) and user-selected target conditions. No trials were excluded from analysis. The overall performance of the navigation system across all trials and planes is summarised in Table 1: median absolute angular deviations were low across all components and anatomical planes; when pooled across all components and anatomical planes, the overall median absolute angular deviation was 1.3° (IQR $0.6\text{--}2.1^\circ$). Using the predefined clinically acceptable threshold of $\pm 3^\circ$, clinical success rates ranged from 83.3% (95% CI 71.3–91.0%) to 100% (95% CI 93.4–100%) across the component-plane combinations. The overall clinical success rate was 90.3% (95% CI 85.6–93.6%).

The median absolute angular deviation for all component-plane combinations was significantly within the clinically acceptable margin of $\pm 3^\circ$ (all $p < 0.00001$). Although the majority of measurements fell within the predefined $\pm 3^\circ$ margin, a small number of deviations

Table 2. Surgical pin positioning accuracy according to target-selection condition.

Target Condition	n	Median Absolute Angular Deviation, ° (IQR)	Range of Angular Deviation, °	Clinical Success Rate, % (95% CI)
Default (0°)	108	1.3 (0.6 to 2.1)	-5.6 to +2.9	91.7 (84.9–95.6)
User-selected	108	1.3 (0.8 to 2.1)	-7.9 to +4.4	88.9 (81.6–93.5)

^aData are presented as the Median Absolute Angular Deviation with interquartile range (IQR) in degrees. Range of angular deviation represents the minimum and maximum signed angular deviation observed. Clinical success was defined as an absolute angular deviation of $\leq 3^\circ$, with 95% confidence intervals calculated for the corresponding proportions. Each target condition comprised 108 component/plane measurements across femoral and tibial pin insertions in the flexion/extension and varus/valgus planes.

exceeding this threshold were observed (Table 1). In addition, similar median angular deviations and clinical success rates were observed between the default and user-selected target conditions (Table 2). There were no statistically significant differences between the two conditions in absolute angular deviation ($p = 0.843$) or clinical success rate ($p = 0.648$).

4. Discussion

The primary objective of this study was to evaluate the accuracy of a smartphone-assisted surgical navigation system for guiding pin placement for cutting guides in TKA using surrogate bone models. The primary outcome was the clinical success rate, defined as an absolute angular deviation of $\leq 3^\circ$. Overall, 90.3% of measurements met this predefined threshold (95% CI 85.6–93.6%). The majority of the 9.7% of pin placements that were outside this range were in the sagittal plane (flexion/extension), meaning that improvements in this plane would further enhance surgical pin placement.

Statistical comparison showed similar performance between the default and user-selected target conditions, with no significant differences in absolute angular deviation or clinical success rate. These findings suggest that target adjustment within the tested -3° to $+3^\circ$ range did not measurably compromise surgical pin positioning accuracy under the controlled conditions of this study.

For context, conventional instrumentation has been reported to have outlier rates ranging from 17% to 78%, while reported ranges for CAS and PSI are 10% to 61% and 0% to 22%, respectively [13]. The 9.7% outlier rate observed in the present study can be considered alongside the broad ranges reported for established alignment technologies. However, these cross-study comparisons should be interpreted with caution because of differences in study design, operators, outcome definitions and measurement methods. The present study was not designed to establish superiority, equivalence, or non-inferiority relative to existing technologies, and direct comparative testing will be required to determine relative performance.

The outliers in this study were primarily confined to the sagittal plane (flexion/extension), with the largest deviation observed in femoral flexion/extension (maximum 7.9°). Review of the outlier cases showed relatively large rotational deviations of the handpiece, suggesting that inconsistent initial rotational positioning may have contributed to the observed flexion/extension errors. This may be particularly relevant for the femur, where axial malrotation of the handpiece can influence sagittal alignment during navigation.

This suggests that longitudinal orientation of the device is more sensitive to user error or morphological variation than coronal alignment. Minor handpiece movement or “toggling” during the transition from navigation to pin insertion may also contribute to sagittal error. Because the device relies on a pin mechanism to conform to the bone surface, any asymmetrical pressure applied during the drilling phase can cause minor rotation of the jig, which translates to an angular error.

To reduce this source of error in future applications, preoperative anatomical landmarks could be incorporated to improve the consistency of initial device orientation. For the femur (which had a lower clinical success rate), incorporating the Whiteside line (perpendicular transepicondylar reference line) [14,15] may help establish a more consistent starting orientation before fine navigation adjustments are made. An alternative would be to provide the rotational position as a target variable on the smartphone application for feedback to the surgeon. Improving initial rotational positioning may also reduce its influence on subsequent flexion/extension alignment.

From a morphological perspective, the presence of prominent peripheral osteophytes (common in osteoarthritis), could alter handpiece seating and introduce unintended flexion or extension. Clinically, meticulous debridement of osteophytes would ensure the pin mechanism captures the intended subchondral topography accurately. Furthermore, the mechanical challenge of the drill bit “skiving” on the hard, sclerotic cortical surface of bone when starting to drill the hole, could cause the pin to migrate slightly before engaging. Future iterations of the

system could include broader stabilizer bases to prevent toggling, varied handpiece sizes to accommodate different surgeon ergonomics, and the use of centring sleeves to mitigate drill bit migration, although this was not found in this surrogate bone test.

Whilst existing advanced technologies aim to improve precision, their widespread adoption is constrained by significant barriers. For CAS and robotics, these platforms offer high degrees of accuracy but impose substantial cost and procedural complexity, which is financially and logistically inaccessible to the majority of surgical centres. For PSI, although presenting a comparatively cheaper alternative, it is limited by a lack of intraoperative flexibility, locking the surgeon into the pre-operative plan. Furthermore there is a lead time for custom manufacturing, and may complicate the potential necessity for revision surgery, as the implanted components are specific to customised parts.

The current study, being a pre-clinical evaluation, is subject to several limitations that must be considered when interpreting the results. Specifically, testing was performed on three in-house fabricated surrogate bone models derived from three independent cadaveric CT datasets, providing some inter-subject anatomical variation. However, these models do not replicate the full range of bone density, soft-tissue constraints, osteophyte morphology, or other surgical conditions encountered clinically. These factors may affect device seating and surgical pin positioning accuracy and should therefore be evaluated in subsequent cadaveric studies. Accordingly, the present study represents a controlled technical validation of guide-pin positioning accuracy rather than a comprehensive assessment of robustness across the full range of clinical scenarios.

In addition, the study's participant pool was limited to three experienced biomechanical engineers with prior training on the navigation system. This selection ensured a standardised assessment of the system's technical capabilities but does not fully represent the varied expertise levels, manual dexterity, or clinical decision-making processes of practising orthopaedic surgeons. Further evaluation with practising orthopaedic surgeons across different levels of experience is therefore required to establish the generalisability of the findings.

Moreover, this study was limited in its scope of outcome evaluation. This study focused solely on the accuracy of guide pin placement, which is a measure of one key component of successful alignment and not the whole process. Therefore, the extent to which the observed surgical pin positioning accuracy translates to final component alignment remains to be established. Further work will need to evaluate the accuracy of the resultant bone resections performed via the guided jigs and, ultimately, the final stability and mechanical axis of the implanted components. Beyond this, patient-reported functional outcomes will need to be evaluated, comparing TKA performed with this device, against TKA performed without it. Furthermore, no direct comparator group was included in this study, thus, the relative performance of the navigation system compared with conventional instrumentation, CAS or PSI remains to be established in future comparative studies.

There are more important steps required before this device can be trialled in patients. The first of these should be to evaluate the system in human cadaveric specimens, where anatomical variability, soft-tissue constraints, bone quality, osteophytes, and realistic surgical exposure can be incorporated. This will allow the robustness of the navigation system to be assessed under conditions more representative of clinical TKA.

5. Conclusion

This pre-clinical study demonstrated that the smartphone-assisted navigation system achieved guide-pin positioning accuracy within the predefined $\pm 3^\circ$ threshold in the majority of trials under controlled surrogate-bone conditions. Direct comparative studies against conventional instrumentation and other alignment technologies are required to establish relative performance. The next necessary phase of research is the validation in human cadaveric specimens with practising orthopaedic surgeons under more clinically representative conditions.

Acknowledgements

This work was supported by the Innovate UK Biomedical Catalyst 10049308.

Infrastructure support for this research was provided by the NIHR Imperial Biomedical Research Centre (BRC) - Biomedical Engineering Theme.

CRedit authorship contribution statement

David Bull: Writing – original draft, Data curation, Formal analysis, Visualization. **Jiaxin Zhang:** Project administration, Methodology, Validation, Visualization, Writing – review and editing. **Shuqiao Xie:** Investigation, Methodology, Writing – review and editing. **Pierluigi Cuomo:** Investigation, Resources. **Gareth G. Jones:** Validation, Resources. **Yuqi Chen:** Investigation, Data curation. **Anthony M. J. Bull:** Supervision, Resources, Writing – review and editing.

Ethical approval

Cadaver-derived imaging data were obtained under institutional tissue bank governance and research ethics approval (HTA Licence 12275; REC approval 22/WA/0214).

References

- [1] Price AJ, Alvand A, Troelsen A, Katz JN, Hooper G, Gray A, Carr A, Beard D. Knee replacement. *Lancet* 2018;392:1672–82. [https://doi.org/10.1016/S0140-6736\(18\)32344-4](https://doi.org/10.1016/S0140-6736(18)32344-4).
- [2] Lošťák J, Gallo J, Zapletalová J. Patient Satisfaction after Total Knee Arthroplasty. Analysis of Pre-Operative and Peri-Operative Parameters Influencing Results in 826 Patients. *Acta Chir Orthop Traumatol Cech* 2016;83:94–101.
- [3] Halawi MJ, Jongbloed W, Baron S, Savoy L, Williams VJ, Cote MP. Patient Dissatisfaction After Primary Total Joint Arthroplasty: The Patient Perspective. *J Arthroplasty* 2019;34:1093–6. <https://doi.org/10.1016/j.arth.2019.01.075>.
- [4] Al-Jabri T, Brivio A, Maffulli N, Barrett D. Management of instability after primary total knee arthroplasty: an evidence-based review. *J Orthop Surg Res* 2021;16. <https://doi.org/10.1186/S13018-021-02878-5>.
- [5] Cottino U, Sculco PK, Sierra RJ, Abdel MP. Instability After Total Knee Arthroplasty. *Orthop Clin North Am* 2016;47:311–6. <https://doi.org/10.1016/J.OCL.2015.09.007>.
- [6] She GR, Zha ZG. Gap balancing versus measured resection in primary total knee arthroplasty: A retrospective cohort study protocol. *Medicine (Baltimore)* 2020;99. <https://doi.org/10.1097/MD.00000000000020017>.
- [7] Plaskos C, Hodgson AJ, Inkpen K, McGraw RW. Bone cutting errors in total knee arthroplasty. *J Arthroplasty* 2002;17:698–705. <https://doi.org/10.1054/arth.2002.33564>.
- [8] Kenanidis E, Paparoidamis G, Milonakis N, Potoupnis M, Tsiridis E. Comparative outcomes between a new robotically assisted and a manual technique for total knee arthroplasty in patients with osteoarthritis: a prospective matched comparative cohort study. *Eur J Orthop Surg Traumatol* 2023;33:1231–6. <https://doi.org/10.1007/s00590-022-03274-3>.
- [9] Iorio R, Bolle G, Conteduca F, Valeo L, Conteduca J, Mazza D, Ferretti A. Accuracy of manual instrumentation of tibial cutting guide in total knee arthroplasty. *Knee Surgery, Sport Traumatol Arthrosc* 2013;21:2296–300. <https://doi.org/10.1007/s00167-012-2005-7>.
- [10] Steffens D, Karunaratne S, McBride K, Gupta S, Horsley M, Fritsch B. Implementation of robotic-assisted total knee arthroplasty in the public health system: a comparative cost analysis. *Int Orthop* 2022;46:481–8. <https://doi.org/10.1007/s00264-021-05203-1>.
- [11] Sassoon A, Nam D, Nunley R, Barrack R. Systematic review of patient-specific instrumentation in total knee arthroplasty: new but not improved. *Clin Orthop Relat Res* 2015;473:151–8. <https://doi.org/10.1007/S11999-014-3804-6>.
- [12] Jones GG, Logishetty K, Clarke S, Collins R, Jaere M, Harris S, Cobb JP. Do patient-specific instruments (PSI) for UKA allow non-expert surgeons to achieve the same saw cut accuracy as expert surgeons? *Arch Orthop Trauma Surg* 2018;138:1601–8. <https://doi.org/10.1007/s00402-018-3031-9>.
- [13] Tandogan RN, Kort NP, Ercin E, van Rooij F, Nover L, Saffarini M, Hirschmann MT, Becker R, Dejour D, Indelli PF, et al. Computer-assisted surgery and patient-specific instrumentation improve the accuracy of tibial baseplate rotation in total knee arthroplasty compared to conventional instrumentation: a systematic review and meta-analysis. *Knee Surg Sports Traumatol Arthrosc* 2022;30:2654–65. <https://doi.org/10.1007/S00167-021-06495-X>.

- [14] Vanin N, Panzica M, Dikos G, Krettek C, Hankemeier S. Rotational alignment in total knee arthroplasty: intraoperative inter- and intraobserver reliability of Whiteside's line. *Arch Orthop Trauma Surg* 2011;131:1477–80. <https://doi.org/10.1007/S00402-011-1329-Y>.
- [15] Paternostre F, Schwab PE, Thienpont E. The combined Whiteside's and posterior condylar line as a reliable reference to describe axial distal femoral anatomy in patient-specific instrument planning. *Knee Surg Sports Traumatol Arthrosc* 2014;22:3054–9. <https://doi.org/10.1007/S00167-014-2836-5>.