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RESEARCH

Enhanced and express workflows in robotic total hip arthroplasty: A paired accuracy study using radiographic validation

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Abstract

Accurate restoration of limb length is an important determinant of functional outcome and patient satisfaction following total hip arthroplasty (THA). Robotic arm-assisted THA enables intraoperative limb-length assessment through different workflows; however, comparative clinical data evaluating their accuracy remain limited. This study aimed to compare the accuracy and agreement of the enhanced and express workflows of a robotic arm-assisted THA system for intraoperative limb-length assessment, using postoperative radiographic measurements as the reference standard. This prospective observational study included 100 consecutive patients undergoing primary robotic arm-assisted THA at a single high-volume centre between January 2024 and January 2025. Each hip underwent paired intraoperative limb-length assessment using both enhanced and express workflows during the same procedure. Postoperative limb-length discrepancy (LLD) was measured on standardized anteroposterior pelvic radiographs at one month. Absolute error between intraoperative and radiographic measurements were compared and analyzed. Eighty-eight hips were available for paired analysis. The enhanced workflow demonstrated lower mean absolute error compared with the express workflow (2.31 mm vs. 3.72 mm). Paired analysis showed a statistically significant reduction in absolute error with the enhanced workflow (median difference −1.0 mm; $p<0.001$). Agreement with postoperative radiographs was higher for the enhanced workflow (CCC = 0.782) than for the express workflow (CCC = 0.620), with narrower limits of agreement. Both workflows provided clinically acceptable intraoperative limb-length estimates during robotic arm-assisted THA. However, the enhanced workflow demonstrated superior accuracy and agreement relative to postoperative radiographic measurements. When operative logistics permit, femoral registration-based workflows may provide greater consistency in limb-length restoration.

Keywords Robotic-assisted total hip arthroplasty · Mako robotic system · Limb length discrepancy · Intraoperative accuracy · Enhanced workflow · Express workflow · Radiographic validation · Bland-Altman analysis · Biomechanical restoration

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Introduction

Total hip arthroplasty (THA) remains the definitive surgical treatment for advanced hip osteoarthritis, providing reliable pain relief and restoration of mobility for most patients [1]. With the growing global prevalence of degenerative hip disease, the demand for THA is projected to rise steadily across both developed and emerging economies [2, 3]. Optimal long-term outcomes depend not only on durable fixation and component orientation but also on accurate restoration of hip biomechanics- particularly limb length and combined offset [4]. Failure to replicate native hip geometry can compromise abductor muscle tension, alter gait mechanics, and lead to complications such as instability, impingement, or persistent pain [5–11].

Robotic technologies have been developed to improve the precision and reproducibility of implant placement in arthroplasty. Among these, robotic arm-assisted THA has gained wide adoption for its ability to translate preoperative three-dimensional planning into controlled intraoperative execution [12, 13]. The Stryker Mako robotic system (Stryker Orthopaedics, Fort Lauderdale, FL) is the most extensively used semi-active platform worldwide, combining haptic feedback and fixed boundary guidance to achieve accurate bone resection and acetabular component positioning within recognized safe zones [14–16].

Two distinct surgical workflows are available within the Mako platform. The enhanced workflow involves registration of both the acetabulum and proximal femur, allowing real-time evaluation of stem alignment, leg length, and combined anteversion during femoral preparation [17]. The express workflow, in contrast, limits robotic assistance to the acetabulum while enabling the surgeon to assess leg length and offset intraoperatively through manual verification. Previous studies have demonstrated that the express workflow can preserve the patient's native offset compared with conventional THA [18], whereas cadaveric analyses suggest that the enhanced workflow improves accuracy of limb length and femoral offset correction [19].

Precise restoration of limb length and combined offset is essential for optimal functional recovery, patient satisfaction, and implant longevity. While both Mako workflows aim to achieve these biomechanical targets, direct clinical comparisons remain limited. This study therefore sought to evaluate the accuracy of the enhanced and express workflows in restoring leg length and combined offset during robotic arm-assisted THA. Secondary objectives included assessment of surgical time, postoperative stability, and workflow-related complications, thereby providing evidence to guide optimal robotic technique selection in contemporary arthroplasty practice.

Methods

This study was a prospective observational cohort study of patients undergoing primary robotic-assisted total hip arthroplasty (THA) at a single high-volume academic arthroplasty centre, between January 2024 to January 2025. All surgeries were performed by a single surgeon using the CT image-based Mako robotic system (Stryker Orthopaedics, Fort Lauderdale, FL). The study was approved by the institutional ethical committee (SIEC/2023/541). Data was collected from the mako surgical planning software, and the institutional picture archiving and communications systems (PACS). Demographic data was retrieved from the prospective institution joint registry. The study is reported according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [20].

Patient Selection

All patients undergoing primary robotic-assisted THA were eligible for inclusion in this study. Inclusion criteria consisted of patients with avascular necrosis of the hip, post-traumatic arthritis, primary osteoarthritis, unilateral hip dysplasia, and arthritis secondary to childhood pathologies such as Perthes disease and SCFE/SUFE.

During the study period, 100 consecutive patients who underwent robotic-assisted THA were eligible for inclusion. 12 patients were excluded (5 patients declined to participate and 7 patients were lost to follow-up).

All patients in this study underwent THA performed by a single surgeon, with uncemented Accolade II stem and uncemented Trident hemispherical acetabular components. All patients undergo routine pre-operative CT scan to generate an image-based surgical plan using the mako 4.0 software for THA. The following measurements were recorded for every patient:

1. Intra-operative limb length discrepancy (LLD) after final component reduction by the Express workflow.
2. Intra-operative LLD after final component reduction by the Enhanced workflow.
3. Post-operative LLD calculated on plain radiograph of the pelvis with both hips, with appropriate magnification on the PACS, measured at 1-month follow-up.

Surgical technique and robotic measurements

All patients were operated in the lateral decubitus position via the posterior approach. Optical array pins were placed in the ipsilateral iliac crest for the pelvic array.

Enhanced workflow

The enhanced workflow involves acetabular and femoral registration. After adequate positioning and skin preparation, three bone pins were inserted over the lateral aspect of the iliac crest via stab incisions for attachment of the pelvic array. The approach was then made, and checkpoints were placed on the lateral aspect of the greater trochanter (femoral checkpoint) and an additional cortical screw placed posteriorly at the inter-trochanteric crest. The femoral optical array is attached to this cortical screw during femoral registration and assessment of LLD/Offset correction (Fig. 1). After dislocation of the hip, femoral bone registration was

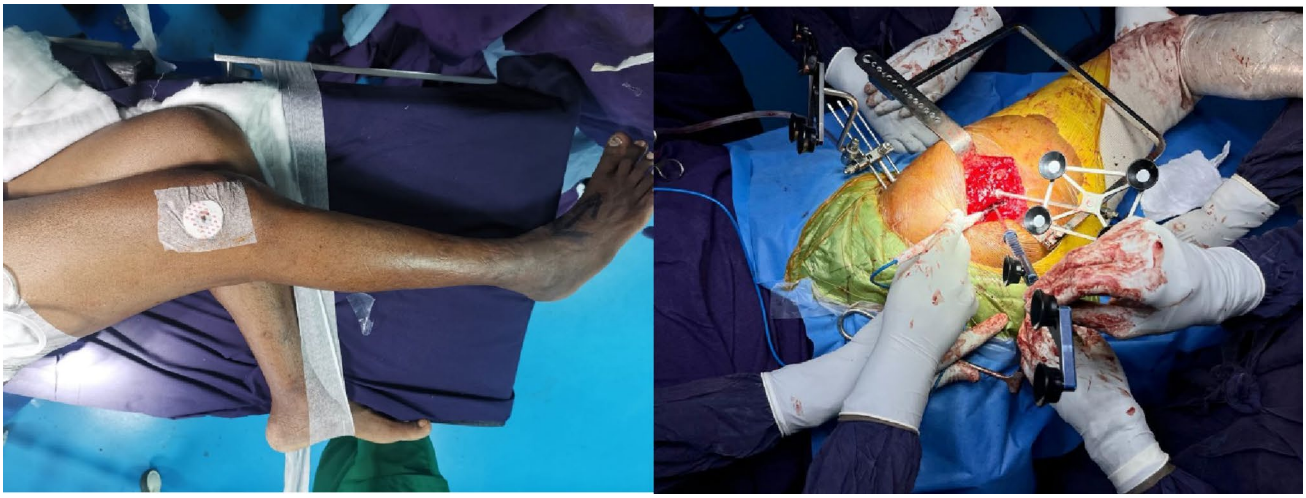

Fig. 1 (left) Electrocardiogram tab placed over the lateral epicondyle of the femur prior to skin preparation for limb length measurement using the express workflow; (right) femoral optical array attached to the cortical screw during femoral registration and assessment of limb length and offset correction using the enhanced workflow

done. Femoral neck osteotomy and sequential femoral broaching was then performed under robotic guidance. The planned stem anteversion, hip length correction and combined offset can be checked throughout this process. After that, we proceeded to register the acetabulum. The acetabular preparation, trial and definitive component insertion is performed by the robotic arm to facilitate optimal acetabular component positioning. Finally, the femoral component is inserted, and the hip length correction and combined offset is checked and recorded.

Express workflow

The express workflow involves only acetabular registration. An electrocardiogram tab was placed over the lateral epicondyle of the femur prior to skin preparation (Fig. 1). A stockinette was then used in the draping process, secured with sterile cling roll, while ensuring that the tab remained palpable. Pelvic pins, as well as pelvic and femoral checkpoints, were placed using the technique described in the enhanced workflow. Hip dislocation was performed after initial registration of the LLD, and femoral neck osteotomy was then performed. The remaining steps of acetabular registration, preparation, trial and definitive component insertion were performed similarly to that of the enhanced workflow. Following this, the femur was broached, trialled, and definitive components were inserted freehand by the surgeon. The surgeon was able to measure the change in leg length and combined offset at any time during the procedure with either the trial or definitive components in situ by reducing the hip and registering with the pointer the palpable tab on the distal ECG Lead reference point and divot on the proximal femoral checkpoint from which the software calculates leg length and combined offset values.

Intra-operative limb length assessment

With the express workflow, the operated lower limb must be kept in an identical position to the contralateral limb during length and offset acquisition, during initial assessment before dislocation and again at the time of trialing. Any change in the position of the limb or distal checkpoint (ECG lead as described) will lead to erroneous values. In the enhanced workflow, the proximal femoral array is linked to a cortical screw which is less likely to move and provides real time estimation of length and offset, irrespective of limb position.

Statistical analysis

Continuous variables were summarized as mean ± standard deviation (SD) or median (interquartile range, IQR) depending on data distribution, and categorical variables were reported as frequencies (%). Normality of continuous data was assessed visually using histograms and Q-Q plots, and analytically using the Shapiro-Wilk test. As the paired differences in absolute error between workflows were not normally distributed (Shapiro-Wilk $p < 0.001$), non-parametric methods were used for paired comparisons. The Wilcoxon signed-rank test was applied to compare absolute errors between the enhanced and express workflows.

Agreement of each intraoperative workflow with the postoperative radiographic reference measurement was quantified using Lin's concordance correlation coefficient (CCC) with 95% CI and visualized using Bland-Altman

Table 1 Summary metrics against postoperative radiograph

Method	*N*	MAE (mm)	RMSE (mm)	Pearson *r*	*p*-value	Lin's CCC	BA LoA Low (mm)	BA LoA High (mm)
Express	88	3.72	4.87	0.655	0.001	0.620	-10.68	7.37
Enhanced	88	2.31	3.78	0.798	0.001	0.782	-8.22	6.04

MAE: Mean Absolute Error; *RMSE*: Root Mean Square Error; *LoA*: Limits of Agreement

Table 2 Superiority testing (paired absolute error)

Outcome/comparison	Test	Effect (median Δ, mm)	*p*-value
Absolute error (mm): Enhanced vs. Express	Wilcoxon signed-rank	-1.00	0.001

plots showing bias and 95% limits of agreement (LoA). Pearson's correlation coefficient (r) was calculated to evaluate linear association, although CCC was considered the primary measure of agreement. Proportional bias was tested by regressing the difference between intraoperative and radiographic measurements on their mean values.

Results

A total of 88 hips were analyzed with paired intraoperative assessments using enhanced and express workflows, each compared against the postoperative radiographic limb-length discrepancy (LLD) as the reference standard. Positive values indicate lengthening and negative values indicate shortening relative to the postoperative radiograph.

Accuracy versus radiograph (Table 1)

The enhanced workflow demonstrated a lower absolute error versus the postoperative radiograph compared with the express workflow. In paired analysis of absolute errors, Wilcoxon signed-rank testing showed a statistically significant advantage for enhanced (median difference Enhanced−Express = -1.0 mm; p=<0.001) (Table 2). Mean signed error (bias) was −1.09 mm for enhanced and −1.66 mm for express. Mean absolute error (MAE) was 2.31 mm for enhanced and 3.72 mm for express, and RMSE was 3.78 mm and 4.87 mm, respectively (Fig. 2).

Agreement and correlation

Lin's concordance correlation coefficient (CCC) indicated stronger agreement with the reference for enhanced (CCC=0.782) than express (CCC=0.620) (Figs. 3 and 4). Pearson correlation with the radiograph was also higher for enhanced (r=0.798, p=<0.001) compared with express (r=0.655, p=<0.001). Bland-Altman analysis showed a mean bias of -1.09 mm for enhanced with 95% limits of agreement from −8.22 to 6.04 mm, and a mean bias of -1.66 mm for express with 95% limits of agreement from −10.68 to 7.37 mm (Figs. 5 and 6).

The enhanced workflow demonstrated superior accuracy and reliability compared with the express workflow for intraoperative assessment of limb-length discrepancy in robotic total hip arthroplasty. Enhanced measurements showed lower absolute error, higher concordance with the postoperative radiographic standard, and narrower limits of agreement. These findings support the use of the enhanced workflow as the preferred method in clinical practice.

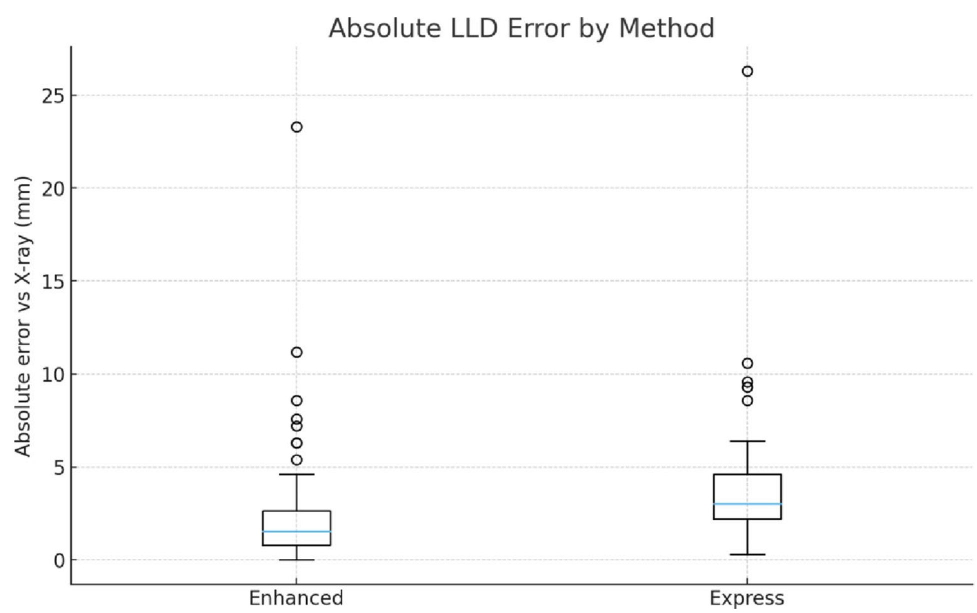

Fig. 2 Boxplots showing mean absolute LLD error versus postoperative radiograph for enhanced and express workflows

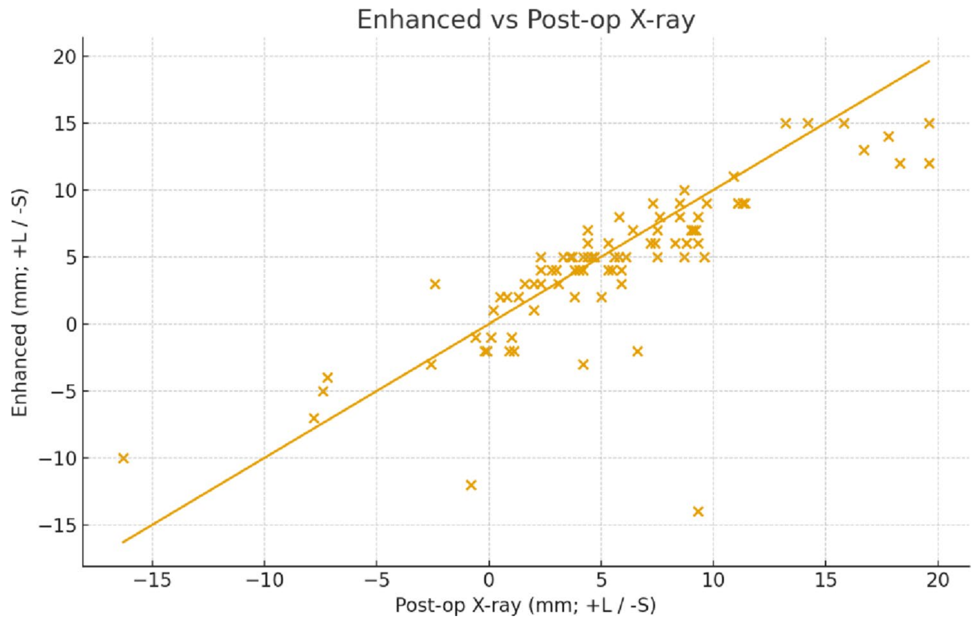

Fig. 3 Enhanced intraoperative LLD versus postoperative radiograph (identity line shown)

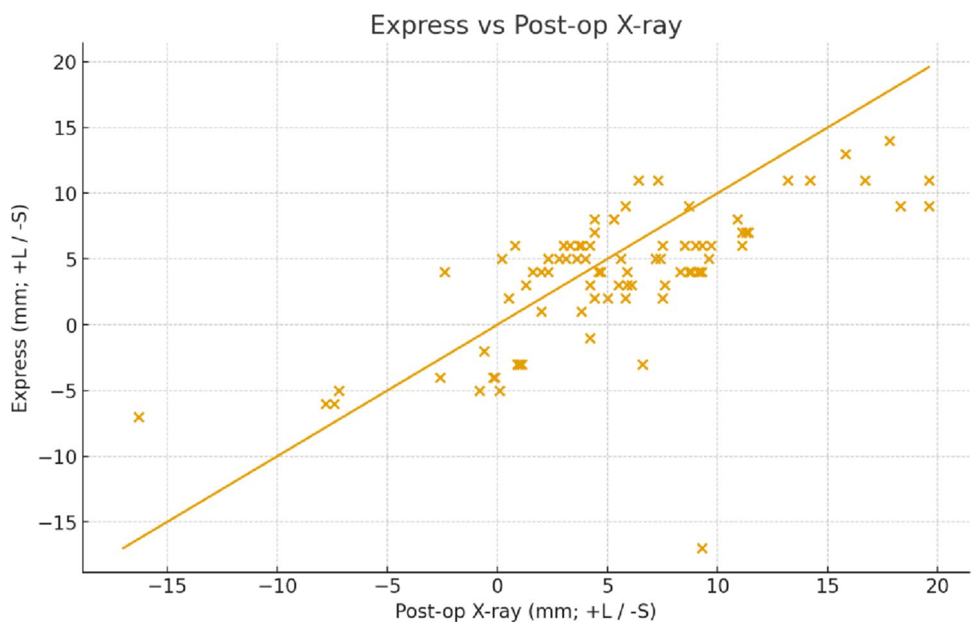

Fig. 4 Express intraoperative LLD versus postoperative radiograph (identity line shown)

Complications

None of the patients reported any post-operative complications including dislocation, fractures, neurological deficits or deep vein thrombosis (DVT).

Discussion

The current study demonstrates that both Mako workflows can achieve reliable intraoperative estimation of limb length during robotic arm-assisted total hip arthroplasty (THA), but the enhanced workflow provided greater accuracy and agreement when compared with the postoperative radiographic standard. The enhanced workflow yielded a lower median absolute error, higher concordance correlation, and narrower limits of agreement, confirming its superiority for precise biomechanical reconstruction.

Precise restoration of limb length and combined offset is fundamental to functional recovery, gait symmetry, and implant longevity following THA [21, 22]. Small discrepancies, particularly lengthening beyond 5 mm, are clinically noticeable to patients and may affect satisfaction [5–7]. In this study, the enhanced workflow reduced mean absolute error to 2.31 mm compared with 3.72 mm in the express workflow, representing a statistically and clinically meaningful improvement. Enhanced registration likely

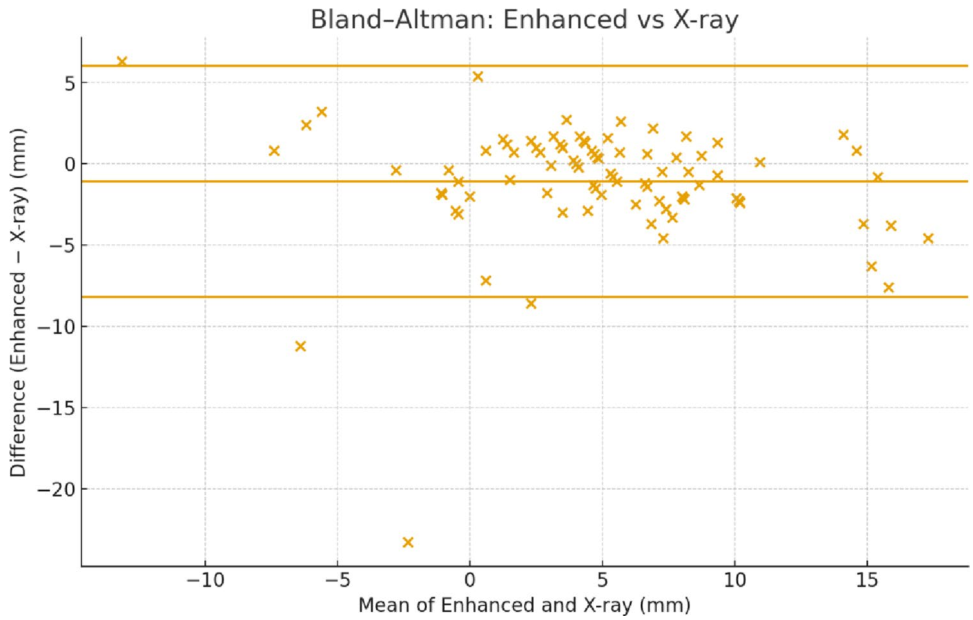

Fig. 5 Bland–Altman plot for enhanced versus postoperative radiograph (bias and 95% limits of agreement)

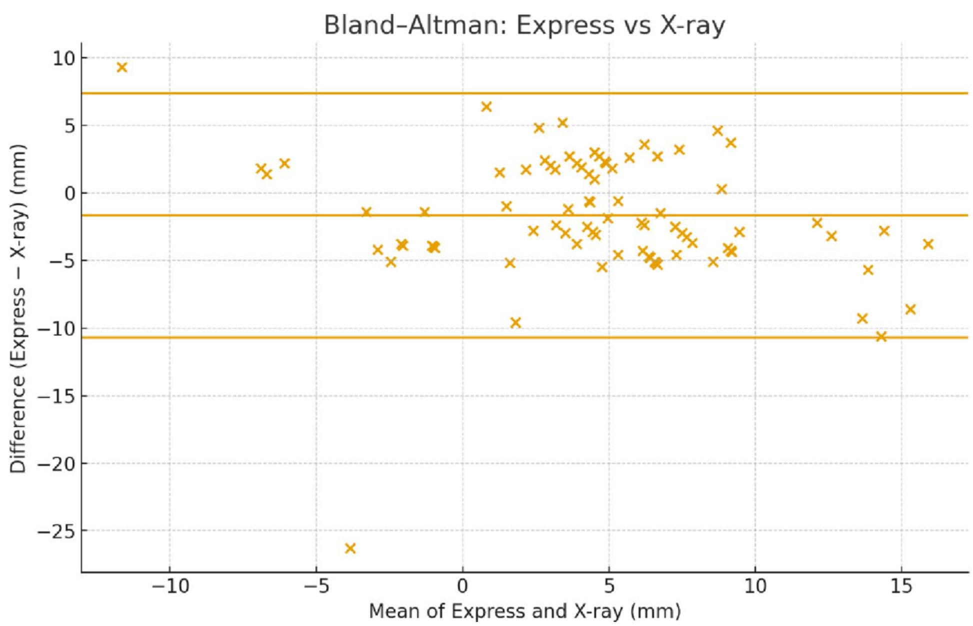

Fig. 6 Bland–Altman plot for express versus postoperative radiograph (bias and 95% limits of agreement)

contributes to this precision by incorporating three-dimensional femoral mapping and allowing verification of the hip centre, stem version, and offset throughout the procedure.

Although both workflows demonstrated high correlation with postoperative imaging, the enhanced protocol offered tighter agreement limits (–8.22 to 6.04 mm versus −10.68 to 7.37 mm) and a higher concordance coefficient (0.782 versus 0.620). These results indicate not only greater accuracy but also improved reproducibility across cases of varying anatomy and bone morphology.

Previous work has highlighted the ability of robotic THA to enhance component alignment and minimize outliers compared with conventional techniques [12–14, 23]. The present study expands on these findings by directly comparing two robotic workflows within the same operative environment. The enhanced workflow's improved accuracy parallels the cadaveric observations of Nawabi et al. [19], who reported superior correction of femoral offset and limb length when both acetabular and femoral mapping were performed robotically. In contrast, the express workflow, although efficient, relies on manual intraoperative assessment, which may explain its slightly greater variability [18].

Our results support the evolving evidence that intraoperative haptic control combined with comprehensive femoral registration enables more reliable reproduction of native biomechanics [23]. Unlike prior reports limited to one workflow or non-paired designs, the present paired comparison eliminates confounding due to inter-patient variability, thereby providing stronger comparative validity.

Clinical and practical implications

Even small improvements in geometric accuracy may have tangible benefits for patient function and implant performance. Restoration of combined offset and hip length improves abductor efficiency and joint stability [9–11, 24, 25]. The enhanced workflow's precision could thus translate into fewer gait asymmetries and reduced risk of trochanteric discomfort or instability. Furthermore, greater reproducibility may shorten the learning curve for surgeons adopting robotic arthroplasty and support consistent results in high-volume practice [26].

Operative efficiency is an important consideration when selecting a robotic workflow, particularly in high-volume arthroplasty practice. Zhao et al. recently reported a significantly longer operative time for the enhanced workflow compared with the express workflow in robotic-assisted THA (93.4 ± 16.4 min vs. 75.2 ± 18.4 min; $p < 0.05$), with no significant differences in limb-length discrepancy, offset restoration, acetabular component orientation, Harris Hip Score, or mid-term complication rates at a mean follow-up of approximately 50 months, suggesting that in patients with relatively normal hip anatomy the additional registration steps may not confer measurable functional advantages while incurring a modest time penalty [27]. In contrast, the present study employed a within-patient paired design with radiographic validation and demonstrates that the enhanced workflow provides superior measurement accuracy, higher concordance, and reduced variability in intraoperative limb-length estimation compared with the express workflow, indicating improved reproducibility rather than merely marginal mean error reduction. Taken together, these findings support an individualized approach to workflow selection, whereby the express workflow may be sufficient in routine anatomical cases prioritizing efficiency, whereas the enhanced workflow may be preferentially justified in complex anatomy or scenarios where maximal biomechanical precision and reproducibility are clinically prioritized.

While the enhanced workflow entails additional steps for femoral registration, the increased setup time is modest and may be outweighed by gains in accuracy, especially in complex scenarios. As robotic utilization continues to expand globally, data-driven workflow selection is essential to balance efficiency, cost, and precision [28, 29].

Strengths and limitations

The main strength of this study lies in its within-patient paired design, which directly compares the enhanced and express workflows under identical operative conditions. Standardized implants, a single experienced robotic surgeon, and uniform postoperative evaluation minimize potential confounding factors. Objective validation using concordance correlation and Bland–Altman analysis further reinforces the robustness of the findings.

However, several limitations should be acknowledged. First, postoperative validation relied on standardized pelvic radiographs rather than CT scans, which may limit accuracy for combined anteversion and offset assessment [30]. Second, all procedures were performed using an uncemented posterior approach, and these findings may not be generalizable to anterior or direct-lateral techniques. Third, the study focused on short-term radiographic accuracy without assessing surgical times, patient-reported or functional outcomes. Finally, single-surgeon data, while improving internal validity, restricts extrapolation to broader surgical settings.

Further work should incorporate CT-based three-dimensional assessment and correlate intraoperative accuracy with patient-reported outcomes and long-term survivorship. Comparative cost-effectiveness analyses between workflows could clarify whether the incremental accuracy of the enhanced protocol justifies the additional intraoperative steps. Expanding such studies to include varied implant systems and approaches will strengthen the generalizability of these findings.

Conclusion

Both the enhanced and express Mako workflows provide accurate intraoperative estimation of limb length during robotic arm-assisted THA. However, the enhanced workflow demonstrated superior agreement with postoperative radiographic measurements and greater measurement consistency. When surgical logistics permit, comprehensive femoral registration should be preferred, particularly in cases of complex anatomy or when precise biomechanical restoration is critical.

Author contributions 1. AA: Conceptualization; Writing - review & editing;2. PM: Writing - original draft; Investigation; 3. TJ: Writing - original draft; Formal analysis;4. DP: Writing - review & editing; Investigation; 5. VBN: Writing - review & editing; 6. AVGR: Writing - review & editing; Conceptualization; Supervision;

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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