

Femoral resection accuracy and precision in manual caliper-verified kinematic alignment total knee arthroplasty

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Abstract

Introduction: The accuracy and precision of bone resections in total knee arthroplasty (TKA) are essential to avoid poor implant positioning, which can lead to component wear, pain, and instability, reducing patient satisfaction and implant survivorship. Technology-assisted TKA techniques aim to improve accuracy but come with added costs, increased operative time, and varying success in clinical outcomes. Caliper-verified kinematic alignment (KA) attempts to restore the joint line by precisely measuring resections to equal implant thickness. We evaluated the accuracy and precision of caliper-verified KA-TKA performed with manual instruments. We hypothesised that this technique would achieve high accuracy and precision, with an average absolute difference between actual and target distal and posterior femoral resection measurements of ≤ 0.5 mm.

Methods: 385 consecutive patients underwent primary unrestricted caliper-verified KA-TKA with manual instrumentation. The thickness of the distal medial (DM), distal lateral (DL), posterior medial (PM) and posterior lateral (PL) femoral condyle resections were measured with a caliper and compared to a target determined by the degree of cartilage loss, saw blade kerf, and femoral component thickness.

Results: The mean differences between the resected and target thicknesses for DM, DL, PM and PL femoral resections were 0.1 ± 0.2 mm, 0.1 ± 0.3 mm, 0.3 ± 0.5 mm and 0.2 ± 0.4 mm, respectively (mean \pm std. dev.). Most femoral resections were within 0.5 mm of the target—97.7%, 94.5%, 85.7% and 89.4% of DM, DL, PM and PL resections, respectively.

Conclusion: Manual caliper-verified KA-TKA achieved highly accurate and precise femoral resections with absolute differences from target that averaged 0.175 mm. This simple, logical, efficient, and reproducible surgical technique may be an option for surgeons contemplating the use of technology-assisted options, such as patient-specific instrumentation or robotic arm-assisted TKA, and surgeons without access to such technologies.

Level of Evidence: Level II.

Abbreviations: BMI, body mass index; CT, computed tomography; DL, distal lateral; DM, distal medial; KA, kinematic alignment; MA, mechanical alignment; MRI, magnetic resonance imaging; PL, posterior lateral; PM, posterior medial; PSI, patient-specific instruction; RAA, robotic arm-assisted; SD, standard deviation; TKA, total knee arthroplasty.

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KEYWORDS

kinematic alignment, patient-specific instrumentation, robotic arm-assisted, total knee arthroplasty

INTRODUCTION

Accurate bone resections are essential for proper component alignment and optimal outcomes in total knee arthroplasty (TKA). Poor implant alignment can lead to increased wear, loosening, pain and instability, reducing patient satisfaction and implant survivorship [1–3]. Technology-assisted TKA techniques were developed to enhance reproducibility and accuracy by limiting human error and reducing outliers. However, their benefits are debatable [1–19], as many variables impact their accuracy and precision [8, 20–27]. Manual instrumentation paired with caliper verification for kinematic alignment (KA) remains a viable and widely used alternative [8, 28–32].

Caliper-verified KA aims to restore each patient's pre-arthritic joint line without soft tissue releases, by removing the same composite thickness of cartilage, bone and saw blade kerf as the implant. The femur defines the kinematic axes of the knee, making the accuracy and precision of the femoral resections critical to the procedure's technical outcome. Mechanical alignment (MA), the primary alternative to KA, applies a uniform alignment target to all patients, disregarding individual joint line variability and resection thickness.

KA-TKA can be performed with manual instrumentation or technology assistance, such as patient-specific instrumentation (PSI-TKA) and robotic arm-assisted (RAA-TKA). PSI-TKA involves customised cutting blocks based on three-dimensional patient models [4, 5], while RAA-TKA employs robotic systems to assist in bone resections within predefined limits [5]. These methods often rely on computed tomography (CT) or magnetic resonance imaging (MRI) to generate three-dimensional models [4]. CT imaging exposes patients to additional radiation [6].

Compared to manual TKA, RAA-TKA and PSI-TKA can increase surgery team anxiety, operative time, and costs [16, 17, 33–39]. Christen et al. [34] estimated that PSI-TKA decreases operative time by five minutes, but increase costs by \$1520 due to the disposable guides and preoperative imaging. Image-based and imageless RAA-TKA increase the operating time by 14 and 25 min, and costs by \$2600 and \$1530, respectively [34]. Over 5 years, robot technology expenses may reach USD 1.362 million due to imaging, disposables, and technical support [37], substantially limiting access across different markets and countries [8]. It is unclear whether the cost of these technologies are justified by improvements in outcomes [16, 17, 34–36, 38, 39].

Reports of the accuracy of TKA technology-assistance are mixed. Some studies indicate that RAA-TKA improves implant positioning without enhancing clinical results [40–46], while PSI-TKA has shown no improvement [47–49] or even inferior accuracy [1–5, 8, 12, 13, 18]. Most studies reporting TKA accuracy and precision focus on angular bone cuts to attain a neutral mechanical axis—the standard of MA. Few studies evaluate the accuracy and precision of resection thickness, making comparisons between manual and technology-assisted approaches difficult.

To establish a baseline, we evaluated the accuracy and precision of caliper-verified KA using manual instrumentation by measuring the mean differences between target and actual femoral resections. We hypothesised that manual KA-TKA would achieve high accuracy and precision, with an average absolute difference measuring ≤ 0.5 mm.

METHODS

The study cohort consisted of all primary TKA patients who consented to participation in a registry database between April 2020 and April 2024. The study enrolled 385 consecutive patients, including 176 women and 209 men. The cohort's mean age and body mass index (BMI) at surgery were 67 years (41–89, standard deviation [SD] 8.59) and 32.4 kg/m² (range 21.46–48.40, SD 4.95) respectively. The average preoperative hip-knee-ankle angle was 175° (range 163°–196°, SD 6.29°. The average tourniquet time was 39.2 minutes (range 21–64, SD 7.06).

Each consenting participant underwent primary TKA with unrestricted KA by a single high-volume surgeon who has performed over 5000 manually instrumented KA-TKA surgeries; no patients were excluded. The following manually instrumented surgical technique has been described previously [28, 30, 32] and was utilised in all cases: tourniquet inflation to 300 mmHg before skin incision, a medial parapatellar arthrotomy, caliper-verified measured femoral resection with posterior referencing, manual cutting blocks with removable saw captures for accurate pre-resection visual assessment, a 1.40 mm saw capture slot with a length of 14.8 mm, Stryker Precision Falcon oscillating-tip saw blades with a thickness of 1.27 mm and cut edge 19.5 mm wide (Stryker Instruments, Portage, MI, USA), cement fixation, and Medacta GMK Sphere (Medacta, Castel San Pietro, Switzerland) implants.

To recreate each patient's native joint line obliquity and knee kinematics, the femur was positioned in neutral rotation to the posterior condyles. The target resection thickness was defined as equal to the thickness of the prosthetic femoral condyle minus one millimetre for bone removal due to the kerf of the saw blade. Adjustments were made for cartilage loss (worn or unworn), assuming a 2 mm normal cartilage thickness. The thicknesses of the distal and posterior condyles of the specific TKA device used in this study were 9 mm and 8 mm, respectively. Therefore, the target for the distal resection was 8 mm for unworn cartilage and 6 mm for worn cartilage, while the target for the posterior resection was 7 mm for unworn and 5 mm for worn. If there was partial thickness cartilage loss, a ring curette was utilised to scrape the remaining cartilage down to bone. The anatomic position of the individual patient's joint line was matched by using a 2 mm shim on any worn condyle. To properly position the 4/1 cutting block, the shim was added to the drill guide to place the distal cut block and to the posterior runners of the anteroposterior sizer for the posterior femoral condyles. No restrictions were implemented based on preoperative alignment.

The following sequence of resections was performed in every case: distal femoral, posterior femoral, anterior and chamfer resections. The distal and posterior resections were measured immediately after the respective cuts were made to allow any necessary corrections before the subsequent resection. The thickness of the distal medial (DM), distal lateral (DL), posterior medial (PM) and posterior lateral (PL) femoral condyle resections were measured with a standardised manual vernier caliper with a resolution of one-half millimetre following a previously established and accepted published technique [20, 50–53]. Recent findings from a controlled and blinded trial indicate that this caliper measurement technique achieves a precision of 0.2 mm, better than the caliper's resolution of 0.5 mm. The technique also shows a negligible bias or systematic error, along with excellent intra-class correlation coefficients for repeatability and reproducibility, exceeding 0.95 (AJ Nedopil, personal communication, 16 February 2025). The difference between the target thickness and actual measured resection was then calculated. A sign was used to distinguish between under- and over-resection, but the *absolute* values were utilised for all mathematical evaluations. Data was captured in a resection verification form (Figure 1) and analysed using Ortho Research Master™ electronic data capture and analysis software (Spokane Joint Replacement Center, Inc., Spokane, WA, USA).

Any actual resection measurement differing from the target by ≥ 1.0 mm was adjusted with either a recut, washer, or block shift according to the following protocol. Undercut distal and posterior femoral condyle resections were recut. Overcut distal condyles

were treated with the placement of a washer under the 4/1 cut block, while overcut posterior condyles were treated with a posterior shift of the 4/1 cut block. Cut block shifts were made in one-millimetre increments. For example, if the target posterior condyle resection was 7 mm, and 8 mm was measured, a hole re-drilling guide would be utilised to drill new cut block pin locating holes to shift the 4/1 block 1 mm posteriorly. The 4/1 block is then impacted into these two new holes, moving its position one mm more posterior. The subsequent cuts would shift the placement of the femoral component 1 mm posteriorly and leave a 1 mm gap at the interface between the posterior condyle bone and implant to be filled with cement.

Ethics

The WCG Institutional Review Board approved this knee registry study. All eligible participants provided written informed consent and good clinical practice regulatory mandates were followed.

RESULTS

Most manual caliper-verified KA-TKA resections were within ± 0.5 mm of the target—97.7%, 94.5%, 85.7% and 89.4% of DM, DL, PM and PL femoral resections, respectively. Moreover, 72.9% of resections were on target, including 82.3%, 76.6%, 64.2% and 68.1% of DM, DL, PM and PL femoral resections, respectively (Table 1).

9.9% of the remaining resections were overcut (exceeded target thickness), and 17.1% were undercut (less than target thickness). The mean *signed* differences (under- vs over-cut) between the target and actual resected thicknesses for the manual KA DM, DL, PM and PL femoral resections were -0.04 ± 0.2 mm (overcut), 0.1 ± 0.3 mm (undercut), 0.1 ± 0.5 mm (undercut), and 0.1 ± 0.4 mm (undercut), respectively (Table 2). The differences ranged from -1 mm to 1 mm for the DM and DL resections and -1 mm to 2 mm for the PM and PL resections; frequency histograms are displayed in Figure 2.

The mean *absolute* differences between the resected and target thicknesses for the DM, DL, PM and PL femoral resections were 0.1 ± 0.2 mm, 0.1 ± 0.3 mm, 0.3 ± 0.5 mm and 0.2 ± 0.4 mm, respectively (mean \pm SD) (Table 3), with an overall average of 0.175 mm \pm 0.350 .

Overcut and undercut resections were selectively corrected with recuts, washers, or posterior shifts (Table 4). Recuts were performed for 6.8%, 10.9%, 2.1% and 1.8% of undercut DM, DL, PM and PL resections, respectively. 89.2% of all recuts were 1 mm or less. One (0.3%) one-millimetre washer was utilised for an overcut DL resection. Posterior shifts were used for 0.5% and 0.8% of PM and PL resections, respectively.



KINEMATIC ALIGNMENT CALIPERED RESECTION VERIFICATION

SURGEON

PATIENT NAME/IDENTIFIER

DATE (DD/MM/YYYY)

OPERATIVE SIDE ☐ Left ☐ Right

WEAR PATTERN ☐ Medial ☐ Lateral ☐ Bicondylar
☐ Isolated Patellofemoral

**FIXED FLEXION
CONTRACTURE**
☐ Y ☐ N _____ mm

DISTAL FEMORAL RESECTION

Target Thickness: 8 mm, Unworn; 6 mm, Worn (no cartilage); + Fixed Flexion Contracture


MEDIAL CONDYLE

☐ Unworn ☐ Worn

MEASURED THICKNESS _____ mm

RECUT ☐ Y ☐ N _____ mm

WASHER ☐ Y ☐ N _____ mm

LATERAL CONDYLE

☐ Unworn ☐ Worn

MEASURED THICKNESS _____ mm

RECUT ☐ Y ☐ N _____ mm

WASHER ☐ Y ☐ N _____ mm


POSTERIOR FEMORAL RESECTION

Target Thickness: 7 mm Unworn; 5 mm Worn


MEDIAL CONDYLE

☐ Unworn ☐ Worn

SHIM ☐ Y ☐ N _____ mm

MEASURED THICKNESS _____ mm

RECUT ☐ Y ☐ N _____ mm

**POSTERIOR
SHIFT 4/1** ☐ Y ☐ N _____ mm

LATERAL CONDYLE

☐ Unworn ☐ Worn

SHIM ☐ Y ☐ N _____ mm

MEASURED THICKNESS _____ mm

RECUT ☐ Y ☐ N _____ mm

**POSTERIOR
SHIFT 4/1** ☐ Y ☐ N _____ mm


TIBIAL RESECTION

Target: equal thickness measured at base of tibial spines
☐ Medial

☐ Lateral

Anterior _____ mm

Posterior _____ mm

☐ Medial

☐ Lateral

Anterior _____ mm

Posterior _____ mm

☐ TIBIAL V-V RECUT _____ deg

☐ TIBIAL SLOPE RECUT _____ deg

☐ TIBIAL RECUT (flat) _____ mm

PATELLA RESURFACING

RESURFACED ☐ Y ☐ N

PATELLA THICKNESS
Pre Cut _____ mm

Post Cut. _____ mm

Resection _____ mm

PCL CONDITION

☐ Intact ☐ Torn ☐ Excised

**IMPLANT
SIZING**

FEMUR SIZE

TIBIA SIZE

INSERT THICKNESS

PATELLA SIZE

☐ CR
☐ CS

LIGAMENT RELEASE
☐ Yes

FIGURE 1 Kinematic alignment calipered resection verification form.

TABLE 1 Manual kinematic alignment overcut and undercut femoral resections ($N = 385$ subjects).

Femoral resection	On target	Overcut	Undercut
Distal medial (DM)	319 (82.9%)	44 (11.4%)	22 (5.7%)
Distal lateral (DL)	295 (76.6%)	16 (4.2%)	74 (19.2%)
Posterior medial (PM)	247 (64.2%)	50 (13.0%)	88 (22.9%)
Posterior lateral (PL)	262 (68.1%)	43 (11.2%)	80 (20.8%)
Average	(72.9%)	(9.9%)	(17.1%)

TABLE 2 Actual mean *signed* accuracy of manual caliper-verified kinematic alignment total knee arthroplasty (TKA) ($N = 385$ subjects).

Femoral resection position	Mean \pm SD (mm)	Range (mm)
Distal medial (DM)	-0.04 ± 0.2	-1 (min.), 1 (max)
Distal lateral (DL)	0.1 ± 0.3	-1 (min.), 1 (max)
Posterior medial (PM)	0.1 ± 0.5	-1 (min.), 2 (max)
Posterior lateral (PL)	0.1 ± 0.4	-1 (min.), 2 (max)

DISCUSSION

Our findings support the primary hypothesis that caliper-verified KA-TKA performed with manual instruments produces excellent femoral resection accuracy and precision, with the absolute difference between target and actual resection measurements averaging 0.175 ± 0.350 mm. We also found a high rate of initial on-target resections of 73%, a total recut rate (all four individual resections summed) of 22%, and a very low washer/posterior shift rate of 1.6%. Our data is consistent with existing manual KA-TKA literature [52, 54], and demonstrates that this technique may be as accurate and precise as any currently available options, including PSI- and RAA-TKA [55–71]. The present report of a large dataset from a single high-volume surgeon adds to the literature additional novel unpublished information.

We performed a literature search for all comparative femoral resection data from technology-assisted TKA studies reporting absolute mean differences between target and actual resections. We identified thirteen RAA-TKA papers [55–58, 60–63, 65, 66, 69–71] and four PSI-TKA papers [59, 64, 67, 68]—including one with two cohorts [67], reporting femoral

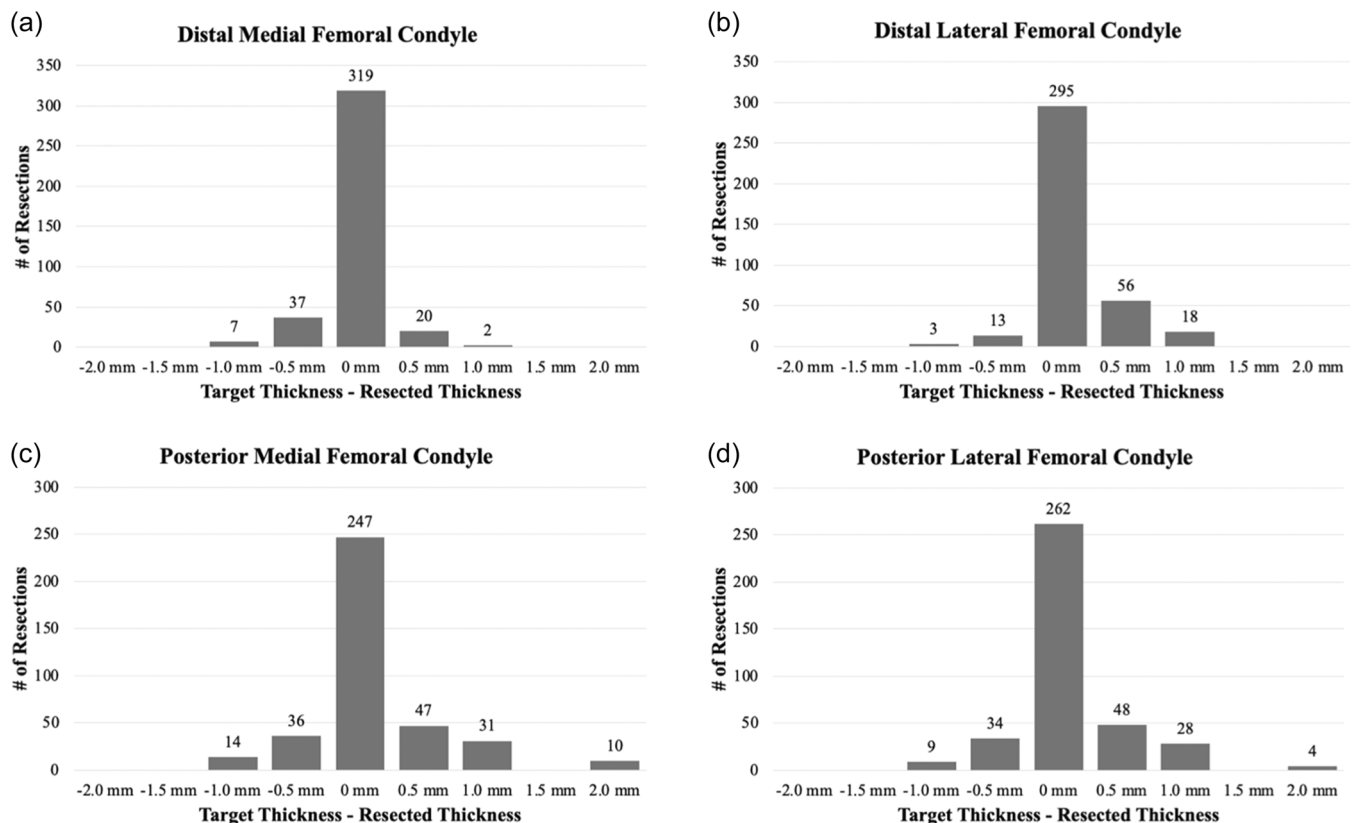
**FIGURE 2** Target and actual resection difference distributions by femoral condyle position.

TABLE 3 Mean *absolute* accuracy of manual caliper-verified kinematic alignment total knee arthroplasty (TKA) ($N = 385$ subjects).

Femoral resection	Absolute mean \pm SD (mm)	Within 0.5 mm	Within 1.0 mm	Within 2.0 mm
Distal medial (DM)	0.1 ± 0.2	97.7%	100%	100%
Distal lateral (DL)	0.1 ± 0.3	94.5%	100%	100%
Posterior medial (PM)	0.3 ± 0.5	85.7%	97.4%	100%
Posterior lateral (PL)	0.2 ± 0.4	89.4%	99.1%	100%

TABLE 4 Use of recuts, washers and posterior shifts to address overcut and undercut resections.

Resection position	Distal medial	Distal lateral	Posterior medial	Posterior lateral
Recut	26 (6.8%)	42 (10.9%)	8 (2.1%)	7 (1.8%)
Mean recut thickness (mm)	1.0	1.0	1.1	1.3
Washer	0 (0.0%)	1 (0.3%)	0 (0.0%)	0 (0.0%)
Mean washer thickness (mm)	-	1.0	-	-
Posterior shift	-	-	2 (0.5%)	3 (0.8%)
Mean posterior shift (mm)	-	-	2.0	1.5

resection accuracy and precision. Of the 13 RAA-TKA papers, five were cadaver studies [56, 57, 61, 63, 70], and eight were clinical [55, 58, 60, 62, 65, 66, 69, 71]. Six studies (three cadaver studies [56, 57, 63] and three clinical studies [58, 62, 66]) were excluded for allowing over- versus under-cuts to cancel each other arithmetically, inappropriately under-reporting mean absolute differences and standard deviations. Among the 13 RAA-TKA studies, two used the MAKO system (one rejected), five used ROSA (two rejected) and six used other systems (two rejected).

Our mean and SD difference from target averaged for all four femoral cuts was 0.175 ± 0.350 , respectively, that of the accepted RAA-TKA literature 0.754 ± 0.697 , and that of the PSI literature 1.133 ± 1.171 , respectively (Tables 5–7). This literature review revealed substantial methodological heterogeneity, a lack of comparative cohorts, and compromised statistical methods, yet all concluded that PSI- or RAA-TKA femoral resections were highly accurate. These shortcomings in the femoral resection accuracy and precision literature limit our analysis and call for better uniformity and improved scientific rigour in reporting future results. Nonetheless, acknowledging the limitations of this thorough comparative literature review, there are no reports of femoral resection accuracy or precision that equal or exceed the data in the present study.

This literature review leads to the conclusion that PSI-TKA is limited in its efficacy and may no longer have a role [1–5, 8, 12, 13, 18] and that RAA-TKA may not be as accurate as we have been led to believe and

deserves more rigorous study. Robotic users may be surprised that the present study and literature review demonstrate that a manual resection technique achieves greater accuracy than reported for CT-based robotic technology. Analysing the robot's several potential error sources [8, 20–27, 72, 73] can help elucidate this discrepancy. One source of error is introduced when creating 3D models from image segmentation. 3D bone models created from 0.625 mm and 1.25 mm CT slices average approximately 0.2 mm smaller than the patient's anatomy [21]. Other error sources are possible, though not explored in the literature, including the reproducibility of the pre-surgical positioning of the femoral component on the 3D model, as well as variations and changes over time in the tolerances of the mechanical joints of the robotic arm. Sources of error may also arise during registration and verification [8, 20, 24, 72], which depend on repeatable anatomic registration as well as stable pin fixation and optical marker position throughout the procedure.

In comparison, the femoral resection guides are securely attached directly to the femur when manual instruments are employed for KA-TKA, eliminating errors inherent to the robotic process, including those related to image acquisition, 3D model construction, component position planning, mechanical tolerances of all articulations, and patient-to-robot registration. Additionally, the cutting blocks and guides used in the present study have a removable saw captures with a larger interface, allowing for maximum pre-cut visualisation and manual surgeon control. Furthermore, manual KA-TKA, which focuses exclusively on the

TABLE 5 Absolute mean accuracy and precision comparison of femoral condyle resections for RAA-TKA compared to KA-TKA with manual instrumentation Welch's *t*-test determined whether the mean accuracy significantly differed, and an F-test determined whether the standard deviations (SD) of RAA significantly differed from manual KA (bold* indicates $p \leq 0.05$, not significant denoted by *italics*).

RAA-TKA study ID	N	Distal medial accuracy \pm SD (mm)	Distal lateral accuracy \pm SD (mm)	Posterior medial accuracy \pm SD (mm)	Posterior lateral accuracy \pm SD (mm)
In vivo studies					
KA-manual instrumentation	385	0.1 \pm 0.2 (ref.)	0.1 \pm 0.3 (ref.)	0.3 \pm 0.5 (ref.)	0.2 \pm 0.4 (ref.)
Rossi et al. [1]	75	0.8* \pm 0.6*	0.9* \pm 0.7*	<i>0.4 \pm 0.6*</i>	0.6* \pm 0.5*
Xia et al. [2]	31	0.9* \pm 0.7*	1.0* \pm 0.7*	0.7* \pm 0.5	1.0* \pm 0.8*
Wan et al. [3]	28	1.3* \pm 0.8*	1.3* \pm 0.9*	0.8* \pm 0.6	0.9* \pm 0.7*
Li et al. [4]	36	0.4* \pm 0.6*	0.5* \pm 0.7*	0.6* \pm 0.8*	0.7* \pm 0.8*
Gamie et al. [5]	44	0.7* \pm 0.6*	0.9* \pm 1.2*	1.1* \pm 1.0*	1.0* \pm 0.8*
Cadaveric studies					
KA-manual instrumentation	385	0.1 \pm 0.2 (ref.)	0.1 \pm 0.3 (ref.)	0.3 \pm 0.5 (ref.)	0.2 \pm 0.4 (ref.)
Li et al. [6]	10	0.4* \pm 0.2	0.4* \pm 0.2	<i>0.3 \pm 0.3</i>	<i>0.3 \pm 0.3</i>
Seidenstein et al. [7]	15	0.7* \pm 0.7*	0.7* \pm 0.7*	0.6* \pm 0.5	0.6* \pm 0.5
Xia et al. [8]	20	0.6* \pm 0.5*	0.6* \pm 0.4*	0.6* \pm 0.4	0.8* \pm 0.7*

Abbreviations: KA, kinematic alignment; RAA, robotic arm-assisted; TKA, total knee arthroplasty.

TABLE 6 Absolute mean accuracy and precision comparison of femoral condyle resections for PSI-TKA compared to KA-TKA with manual instrumentation Welch's *t*-test determined whether the mean accuracy significantly differed, and an F-test determined whether the standard deviations (SD) of PSI significantly differed from manual KA (bold* indicates $p \leq 0.05$, not significant denoted by *italics*).

PSI-TKA study ID	N	Distal medial accuracy \pm SD (mm)	Distal lateral accuracy \pm SD (mm)	Posterior medial accuracy \pm SD (mm)	Posterior lateral accuracy \pm SD (mm)
KA-TKA manual instrumentation	385	0.1 \pm 0.2 (ref.)	0.1 \pm 0.3 (ref.)	0.3 \pm 0.5 (ref.)	0.2 \pm 0.4 (ref.)
Wernecke et al. [68]	118	0.9* \pm 1.3*	0.9* \pm 1.3*	1.5* \pm 2.1*	0.8* \pm 1.2*
Kim et al. [59]	30	0.8* \pm 0.4*	0.7* \pm 0.4*	0.8* \pm 0.5	0.8* \pm 0.5
Kang et al. (MRI) [67]	36	0.9* \pm 0.7*	1.4* \pm 0.9*	1.1* \pm 0.9*	1.3* \pm 0.9*
Kang et al. (CT) [67]	35	1.2* \pm 0.7*	1.6* \pm 1.0*	1.4* \pm 0.9*	1.6* \pm 0.8*
Yamamura et al. [64]	45	0.6* \pm 0.7*	1.4* \pm 1.2*	1.8* \pm 0.9*	1.7* \pm 1.0*

Abbreviations: KA, kinematic alignment; PSI, patient-specific instrumentation; TKA, total knee arthroplasty.

anatomic landmarks within the knee joint, avoids errors inherent in intramedullary or extramedullary guides targeting long-axis limb alignment [8, 20, 74].

Howell compared the femoral resection accuracy of more and less experienced surgeons performing unrestricted caliper-verified manual KA to PSI- and RAA-TKA techniques, demonstrating that surgeons with less experience were statistically equivalent or more accurate compared to PSI- and RAA-TKA, and that surgeons who had performed more than fifty caliper-verified KA surgeries were significantly more accurate [54]. Thus, the femoral resection accuracy of caliper-

verified KA with manual instrumentation does not depend on surgeon experience to match or exceed the accuracy of PSI- and RAA-TKA. Another report corroborates a minimal learning curve to obtain resection accuracy and reveals that operative time drops substantially over the course of the first thirty cases [52].

One weakness of the present study is that the analysis is limited to femoral resections. The tibial resection is also an essential element. We focused on the femur as the three-dimensional shape of the tibial plateau creates measurement challenges, and there is a lack of studies with similar methodology in the literature. Analysis of

TABLE 7 Absolute mean accuracy comparison of four femoral condyle resections combined for KA-TKA with manual instrumentation compared to RAA-TKA cadaver studies, RAA-TKA clinical studies, RAA-TKA studies combined, and PSI-TKA Welch's *t*-test determined whether the mean accuracy significantly differed from manual KA (bold* indicates $p \leq 0.05$, not significant denoted by *italics*).

Study ID	N	Four femoral resections combined accuracy \pm SD (mm)
KA-TKA manual instrumentation	385	0.175 \pm 0.350 (ref.)
RAA-TKA cadaver [61, 70]	45	0.583* \pm 0.504*
RAA-TKA clinical [55, 60, 65, 69, 71]	214	0.795* \pm 0.729*
RAA-TKA combined [55, 60, 61, 65, 69–71]	259	0.754* \pm 0.697*
PSI-TKA combined [59, 64, 67, 68]	264	1.133* \pm 1.171*

Abbreviations: KA, kinematic alignment; PSI, patient-specific instrumentation; RAA, robotic arm-assisted; TKA, total knee arthroplasty.

tibial resections may require a different measurement methodology, possibly with three-dimensional imaging and/or computer-assisted algorithms.

Another limitation of the present study is the lack of clinical outcomes; however, the scope of this study was focused narrowly on the technical performance of the femoral resections, evaluating their accuracy and precision, utilising the manual tools and techniques described in the Methods, and contrasting our results with all comparable data in the literature. Clinical outcomes are outside of the scope of this manuscript and are not present in the comparable studies, though warrant future study.

Our findings evaluate resection data produced from a specific surgical technique (unrestricted caliper-verified KA) and thus may not be directly comparable to data obtained with other techniques such as MA. KA and MA aim for different overall results and have different bone resection targets [31]. KA attempts to restore individual patients' natural kinematic axes, while MA seeks to achieve a neutral mechanical axis and a perpendicular joint line. We avoid directly comparing these alignment philosophies by focusing solely on the accuracy and precision of the technical performance of the femoral resections. Bias is eliminated by limiting the analysis to target versus actual resected measurements, irrespective of differing alignment philosophies and surgical techniques.

Despite disparate alignment goals or surgical techniques, each resection must be accurate and

repeatable. Resections performed with a saw blade-controlled manually or by a robotic arm-will inevitably have some inherent error. There must be some tolerance built into the saw capture, such that the dimension of the capture is slightly larger than the saw blade, which will cause some variability, regardless of whether a human or robot is controlling the saw blade. Additionally, in the case of a saw blade operated by a robotic arm, there is also inherent variability or "slop" built into the system [8, 20–27, 50, 72, 73, 75].

Regardless of technique, the threshold for recutting an undercut resection or supplementing an overcut resection with a washer or shift may affect accuracy. We used a recut threshold of ≥ 1.0 mm in the present study. Other surgeons using this KA technique may conduct recuts for different target versus actual difference thresholds, potentially resulting in variations in accuracy and precision.

Most PSI- and RAA-TKA studies do not include resection thickness measurements; instead, they limit their reported data to the accuracy of angular targets, with that target generally being the achievement of a neutral HKA. Therefore, the accuracy of manual KA procedures in terms of matching an alignment target should be evaluated and compared to the RAA-TKA literature, but this is outside of the scope of the present manuscript, and would require the calculation of a target postoperative HKA as well as target joint line obliquity.

One could argue that the outcomes of manually instrumented, caliper-verified KA do not support its widespread adoption; however, the literature is replete with reports demonstrating excellent mid- to long-term results [2, 76–91]. In contrast, the most defensible conclusions supported by the knee robotics literature are that alignment outliers and iatrogenic soft tissue injury may be reduced, and possibly, very short-term outcomes, such as length of stay, improved. Most notably, no blinded, randomised trials or comparative cohort trials demonstrate clinically meaningful improvements in mid- to long-term clinical outcomes or implant survivorship, and much literature concludes the contrary [6, 7, 9–11, 14–17, 19, 92–97].

Although evidence suggests a relationship between the accuracy of bone resections and patient outcomes, the degree of accuracy required for positive outcomes remains unknown. There is no consensus regarding the best alignment target, and until that is conclusively determined, the evaluation of accuracy as the primary focus is misguided, without being sure of the best target. The rapid adoption of technology assistance in knee arthroplasty, primarily RAA-TKA, has been driven mainly by non-scientific media promotion and consequent consumer demand [6, 98]. Future studies must explore whether differences in bone resection accuracy translate to clinically

meaningful differences in outcomes, including assessing the point of diminishing returns, where increased femoral resection accuracy may no longer yield benefits in outcomes.

CONCLUSION

Caliper-verified kinematic alignment TKA performed with manual instrumentation produces excellent femoral resection accuracy and precision, with the absolute difference between target and actual resections averaging less than 0.175 mm. These results match or exceed the resection accuracy of PSI- and RAA-TKA, questioning the necessity of these costlier technologies. Future randomised trials are needed to clarify the impact of TKA femoral resection accuracy on long-term outcomes, and whether technology-assistance is beneficial.

AUTHOR CONTRIBUTIONS

David F. Scott designed the study and performed writing—original draft and review. Emma N. Horton participated in review and performed data collection and analysis. Both authors read and approved the final manuscript.

CONFLICT OF INTEREST STATEMENT

The corresponding author receives research support from Medacta and MicroPort.

DATA AVAILABILITY STATEMENT

The data presented in this study may be available upon request to the corresponding author. The data are not publicly available due to privacy and ethical reasons.

ETHICS STATEMENT

This study was approved by the Institutional Review Board of WCG IRB, study approval # 20200306. All patients signed informed consent.

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