

The one-millimetre varus knee: titrating femoral rotation to the medial flexion gap in functional-alignment robotic total knee arthroplasty

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Abstract

Purpose. The varus knee is medially tight and has classically been balanced by stepwise soft-tissue release, which risks over-release. We tested whether, in functional-alignment (FA) robotic total knee arthroplasty (TKA), femoral rotation titrated to the medial gap balances the varus knee to within one millimetre with only a mild release, and derived a bedside rule.

Methods. Observational analysis of 65 consecutive varus primary FA robotic TKAs by a single surgeon using an image-based platform. Femoral rotation, medial–lateral (M–L) gap asymmetry across preoperative, planned and final states, the graded release and balance were analysed; regression related rotation to medial flexion tightness; Wilson 95% confidence intervals; no imputation.

Results. Femoral external rotation was titrated to the medial flexion gap — approximately 1.9° plus 0.34° per millimetre of tightness ($\rho = -0.57$; $R^2 = 0.26$; $p < 0.001$) — giving a simple bedside rule. With this, the medial release stayed mild in 64/65 knees (no escalation). M–L asymmetry fell from 3.8/4.5 mm (extension/flexion) to 0.4/0.3 mm — below one millimetre in 83%/93% of knees — mostly by planning. Functional balance reached 98% and strict-mechanical balance 91%; WOMAC improved from 74.6 to 2.5 and FJS-12 reached 95.2 at one year.

Conclusion. In the varus knee, rotating the femur to the medial gap — rather than releasing more soft tissue — balances the knee to within one millimetre with only a mild release. A simple titration chart and playbook translate this into daily practice.

Introduction

Functional alignment (FA) individualises component positioning within physiological limits, respecting the patient's constitutional anatomy rather than imposing systematic mechanical neutrality [1, 2]; it sits among the established alignment philosophies and aims to reconstruct a balanced knee within a stable flexion–extension envelope [3, 4]. Image-based robotic platforms quantify the compartmental gaps before resection and allow measured, reproducible balancing [5, 6] toward the physiological laxity targets of the knee [7, 8].

The varus knee poses the paradigmatic balancing problem: it is medially tight, and the classical solution is a stepwise medial soft-tissue release — deep medial collateral ligament (MCL), posterior oblique ligament, semimembranosus and, if needed, superficial MCL or pie-crusting [9–11]. Effective as it is, this sequence carries a real risk of over-release of the superficial MCL, particularly in severe varus, with the instability that follows. Robotic FA introduces a second, quantifiable lever — femoral component rotation — and small changes in component position are known to modulate soft-tissue balance [12]. If rotation can be matched to the measured medial gap, the surgeon may reach a balanced knee while keeping the release minimal.

We therefore analysed a consecutive series of varus FA robotic TKAs to test three practical questions: whether femoral rotation is titrated to the medial gap in a way that yields a usable bedside rule; whether, under that strategy, the medial release stays mild; and how closely and where in the workflow medial–lateral gap symmetry is restored. Building on a previously reported classification of preoperative gap phenotypes from this cohort [13] and on evidence that planned resection scales with deformity [14], we translate the findings into a titration chart and a varus playbook for daily use.

Materials and methods

This observational study analysed prospectively recorded operative data from consecutive primary FA robotic TKAs performed by a single knee surgeon at a tertiary referral centre, reported per the STROBE statement [15]. Institutional ethics committee approval and informed consent were obtained (approval number on the title page). The 65 varus knees analysed here are drawn from our institutional, consecutive FA robotic TKA program, part of which was reported in an earlier derivation study [13]; the present series is larger and varus-focused (Table 1), and no data were imputed.

All procedures used an image-based robotic platform (medial parapatellar approach). Gap measurements were captured at the three states used in this analysis: preoperative (the registered arthritic knee, before any release or virtual tensioning), planned (the finalised virtual component plan) and final (after bone cuts and trial insertion). Standardized soft-tissue management and calibrated tensioning were performed between the preoperative and planned states. Gaps were measured with calibrated distractors in the medial and lateral compartments, independently, in extension and at 90° of flexion; posterior osteophytes were removed routinely. Medial–lateral (M–L) gap differences were computed as medial minus lateral, so negative values denote a tighter medial compartment.

Medial management followed a stepwise, gap-titrated sequence guided by the robotic display and graded by extent (Table 2): mild – osteophyte removal with limited subperiosteal elevation of the deep MCL and posterior oblique ligament, preserving the superficial MCL [9]; moderate – extension to the posteromedial capsule or semimembranosus, or controlled pie-crusting / multiple-needle puncture of a persistently tight medial gap [11]; and major (escalation) – superficial-MCL release or mid-substance pie-crusting, reserved for residual asymmetry (> 3 mm) or malalignment (> 3°) after component position was optimised [10]. Superficial-MCL over-release was deliberately avoided and no posterior capsulotomy was performed.

We recorded the hip–knee–ankle (HKA) angle and its reducibility, femoral external rotation, tibial slope, M–L resection asymmetry, polyethylene thickness, and the medial and lateral extension and flexion gaps at the preoperative, planned and final states. Balance was defined as strict mechanical (M–L gap difference ≤ 1 mm in extension and flexion) or functional (M–L symmetry within the FA envelope). Functional coronal alignment was pre-specified as a final hip–knee–ankle (HKA) angle within $\pm 3^\circ$ of neutral – up to 3° of residual varus or valgus – reflecting the FA intent to preserve mild constitutional alignment rather than force mechanical neutrality. Clinical outcomes were the WOMAC index [16] and the

Forgotten Joint Score-12 (FJS-12) [17] to one year. Continuous variables are summarised as mean $\pm$ standard deviation and proportions with Wilson 95% confidence intervals. Femoral rotation was related to the preoperative medial flexion tightness by Spearman correlation and ordinary least-squares regression (reported as intercept and slope with R^2), and preoperative-versus-final asymmetry by the Wilcoxon signed-rank test. Analyses used Python 3.12 (NumPy, SciPy, statsmodels); no imputation was applied.

Results

The 65 varus knees had a mean age of 73.0 ± 7.7 years and were 73.5% female (linked subgroup); the preoperative absolute HKA was $7.28 \pm 3.61^\circ$ with a mean reducibility of 5.9° , and implants were predominantly cruciate-substituting (Table 1).

Femoral external rotation was titrated to the medial flexion gap: the tighter the medial flexion compartment, the greater the external rotation applied ($\rho = -0.57$; $p < 0.001$; $n = 63$). Regression yielded a simple bedside rule — femoral external rotation $\approx 1.9^\circ + 0.34^\circ$ per millimetre of medial flexion tightness ($R^2 = 0.26$) — corresponding to about 3.3° at 4 mm and 4.7° at 8 mm of tightness; the mean applied rotation was $3.44 \pm 1.92^\circ$ (Fig. 1).

This rule is a starting estimate rather than a deterministic target: the relationship was moderate ($R^2 = 0.26$) and the 95% prediction band was wide — for example, at 5 mm of medial flexion tightness the predicted external rotation was 3.6° (95% prediction interval 0.3° – 7.0°). It describes the rotation applied across this single-surgeon series and is intended to guide, not replace, per-knee titration on the live gap.

Under this rotation-led strategy, the standardized medial release remained mild in 64 of 65 knees, with a single moderate release and no escalation (Table 2). Medial–lateral gap asymmetry was corrected progressively and converged toward one millimetre (Fig. 2): the absolute extension asymmetry fell from 3.81 mm preoperatively to 1.50 mm at planning and 0.38 mm at trialing, and the flexion asymmetry from 4.45 to 1.22 and 0.29 mm (preoperative versus final $p < 0.001$ for both), with roughly two-thirds to three-quarters of the correction already achieved at planning. At the final state, the M–L asymmetry was below one millimetre in 83% of knees in extension and 93% in flexion.

The final HKA was $2.3 \pm 1.7^\circ$ of residual varus (range 2.5° valgus to 5.5° varus), within the $\pm 3^\circ$ functional envelope in 72% of knees. Functional gap balance was reached in 98% of assessable varus knees and strict-mechanical balance in 91%. At one year, WOMAC improved from 74.6 ± 23.0 to 2.5 ± 4.4 and FJS-12 reached 95.2 ± 15.9 .

Table 1
Characteristics of the varus cohort (n = 65)

Characteristic	Value
Age, years (linked subgroup)	73.0 ± 7.7
Female, % (linked subgroup)	73.5
Preoperative HKA , °	7.28 ± 3.61
Reducibility, °	5.9
Femoral external rotation, °	3.44 ± 1.92
Final HKA, ° (+ = varus)	2.3 ± 1.7 (72% within ± 3°)
Standardized medial release, n	Mild 64; Moderate 1; Major 0

HKA hip–knee–ankle. Demographic data refer to the linked subgroup. Implants were predominantly cruciate-substituting.

Table 2
Graded medial soft-tissue management

Grade	Technique	Indication
Mild	Osteophyte removal + limited subperiosteal deep-MCL / posterior oblique ligament elevation; superficial MCL intact	Most varus knees (64/65 here)
Moderate	Extension to posteromedial capsule / semimembranosus, and/or controlled pie-crusting or multiple-needle puncture	Persistently tight medial gap (1/65 here)
Major (escalation)	Superficial-MCL release or mid-substance pie-crusting	Residual asymmetry > 3 mm or malalignment > 3° after component optimisation (0/65 here)

MCL medial collateral ligament. Superficial-MCL over-release was deliberately avoided; no posterior capsulotomy was performed [9–11]. Grades reflect a protocolised sequence; the data do not define millimetre thresholds between grades.

Discussion

The central, practical message of this study is that in the varus knee the femur can be externally rotated to the medial gap instead of the medial sleeve being released to it. Specifically, it is external rotation of the femoral component that opens the tight medial flexion gap relative to the lateral side, equalising the flexion space by bone rather than by release. Femoral external rotation was titrated to the preoperative medial flexion tightness in a near-linear fashion — about 0.34° per millimetre — and, under this strategy, the standardized medial release remained mild in all but one knee, with no escalation. The knee

nonetheless converged to a medial–lateral asymmetry below one millimetre in the large majority of cases, and clinical outcomes at one year were excellent.

These two levers act on different parts of the flexion–extension envelope. The standardized medial release is directed at the extension gap – it is advanced until the medial and lateral extension gaps converge – and thus addresses the coronal, extension-side tightness that dominates the varus deformity [9, 11]; femoral external rotation, by contrast, acts on the flexion gap, opening the medial side to match the lateral. This division of labour is visible in the asymmetry trajectory (Fig. 2), where the extension and the flexion asymmetry both converge toward one millimetre but through different adjustments – release for the former, rotation for the latter. Treating the correction as two compartment-specific levers, rather than a single soft-tissue manoeuvre, is what allows the medial release to remain mild while the flexion gap is still equalised.

The most usable output is the titration rule and chart (Fig. 1): femoral external rotation $\approx 1.9^\circ + 0.34^\circ$ per millimetre of medial flexion tightness. It offers the surgeon a starting estimate at the console – roughly $3\text{--}5^\circ$ across the common range of medial tightness – and reframes the varus balancing decision from “how much to release” toward “how much to externally rotate”, complementing the classical release-based teaching [9–11] and the evidence that small component-position changes modulate balance [12]. Because the relationship is moderate ($R^2 = 0.26$), the chart is a guide rather than a formula: rotation is one of several coupled adjustments and must still be titrated to the live gap on the display. Importantly, because greater femoral external rotation can compromise patellofemoral tracking, the rotation applied to balance the medial flexion gap should be weighed against patellar tracking and tilt – the larger the external rotation, the greater the attention required to preserve patellofemoral congruence.

The trajectory of asymmetry has an equally practical corollary. More than 4 mm of preoperative medial–lateral asymmetry collapsed to about 0.3 mm at trialing, with the majority of the correction already achieved at the planned state. The planned state therefore functions as a decision checkpoint – if the medial–lateral gap is not approaching one millimetre there, the surgeon should revisit rotation, resection or a graded release before cutting, rather than expecting the trial to rescue the balance. Reporting the preoperative, planned and final states together makes this checkpoint explicit and auditable, resting on the preoperative phenotypes characterised previously [13, 14].

For the reader, the varus playbook (Fig. 3) condenses the approach: measure the medial and lateral gaps; set femoral external rotation from the medial flexion tightness using the chart; perform a mild graded medial release for medial extension tightness, escalating only for residual asymmetry > 3 mm or malalignment $> 3^\circ$; and confirm a sub-millimetre balance at planning before cutting. High balance rates and robust one-year outcomes accompanied this routine, and robotic assistance more broadly reduces alignment outliers [18], supporting the reproducibility of a console-level, gap-guided rule.

This study has limitations. It is observational, single-surgeon and single-centre, which limits external validity, and it shares its cohort with our derivation study [13], although it addresses a distinct, practice-oriented question with non-overlapping primary outcomes. Femoral rotation is set to balance the flexion

gap, so its correlation with the medial gap is partly expected by design; the contribution is quantifying its magnitude as a usable rule. The graded-release intensities were surgeon-assigned and not tested for inter-observer reliability, and because only one moderate and no major releases occurred, the millimetre thresholds between grades cannot be derived from these data and are presented as a protocol to be validated. Intraoperative gaps are a surrogate for weight-bearing radiographic balance, and patient-reported outcomes were available for part of the cohort at one year and are descriptive. Patellofemoral tracking was not systematically recorded and could not be correlated with the applied rotation. The titration rule and playbook guided balancing within this single-surgeon series; their value must be re-evaluated when extrapolated to other surgeons, robotic platforms and populations before being generalised. Multicentre, prospective validation of the titration rule is warranted; the strengths are a consecutive varus series with complete preoperative, planned and final gap data and transparent denominators.

Conclusion

In the varus knee undergoing FA robotic TKA, externally rotating the femur to the medial gap — about 1.9° plus 0.34° per millimetre of medial flexion tightness — balances the knee to within one millimetre while keeping the medial release mild, and most of the correction is achieved by the planning stage. Summarised as a titration chart and a varus playbook, this offers a simple, gap-guided rule for balancing the varus knee at the console.

Declarations

Author Contribution

Author contributions: Conceptualization: E.F.T., L.H.C.Jr. Investigation and data curation: E.F.T. , L.F.M.S, M.B.J.G. Writing - original draft: E.F.T. and P.H.O.G. Writing - review and editing: all authors. All authors read and approved the final manuscript.

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Figures

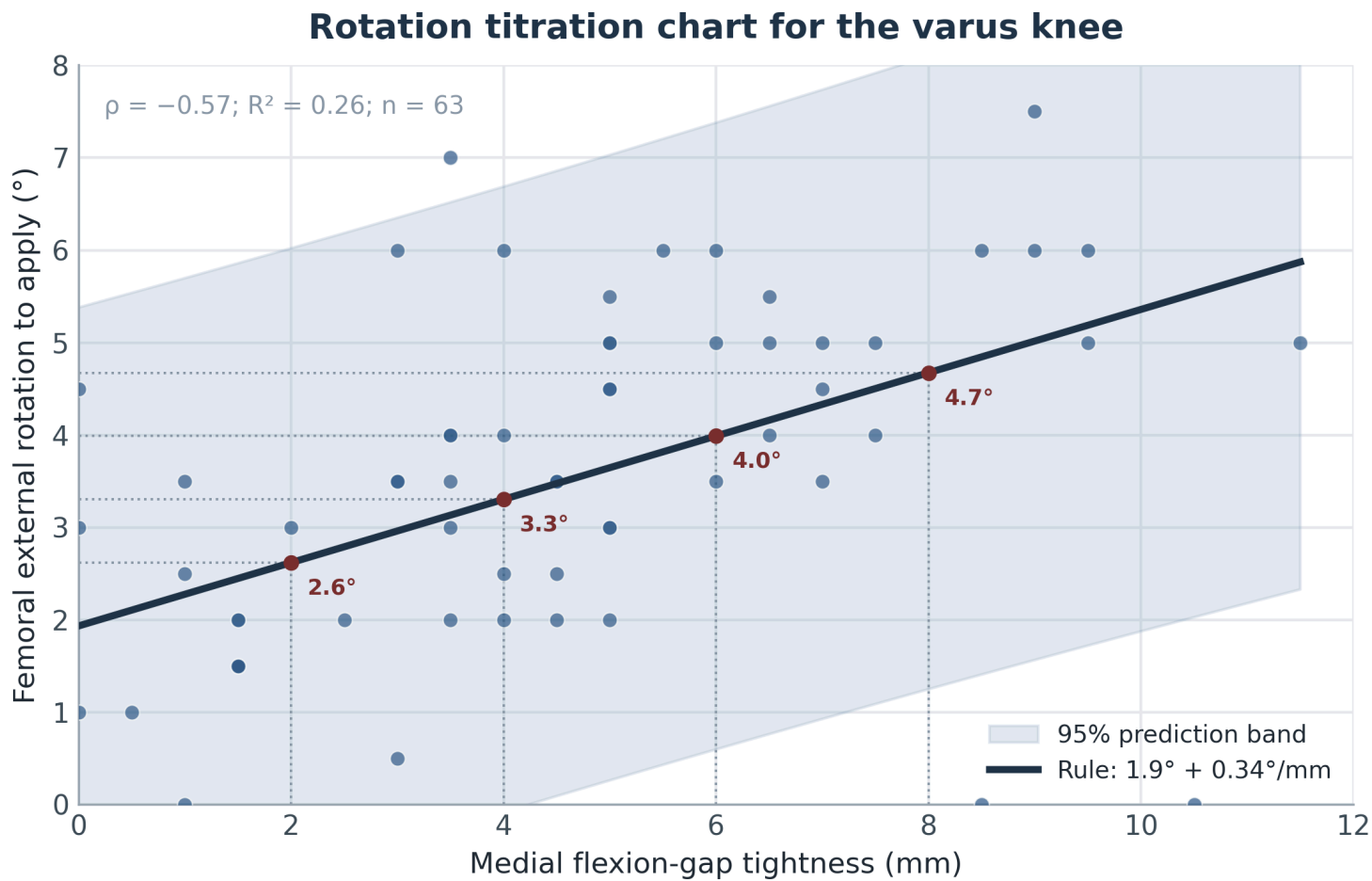


Figure 1

Rotation titration chart for the varus knee. Femoral external rotation applied versus the medial flexion-gap tightness (each point one knee); the line is the fitted rule ($\approx 1.9^\circ + 0.34^\circ$ per mm) with its 95% prediction band, and the marked reads give the estimate at 2, 4, 6 and 8 mm of tightness ($\rho = -0.57; R^2 =$

0.26; n = 63). The rule gives a starting estimate; the wide prediction band means rotation must still be titrated to the live gap.

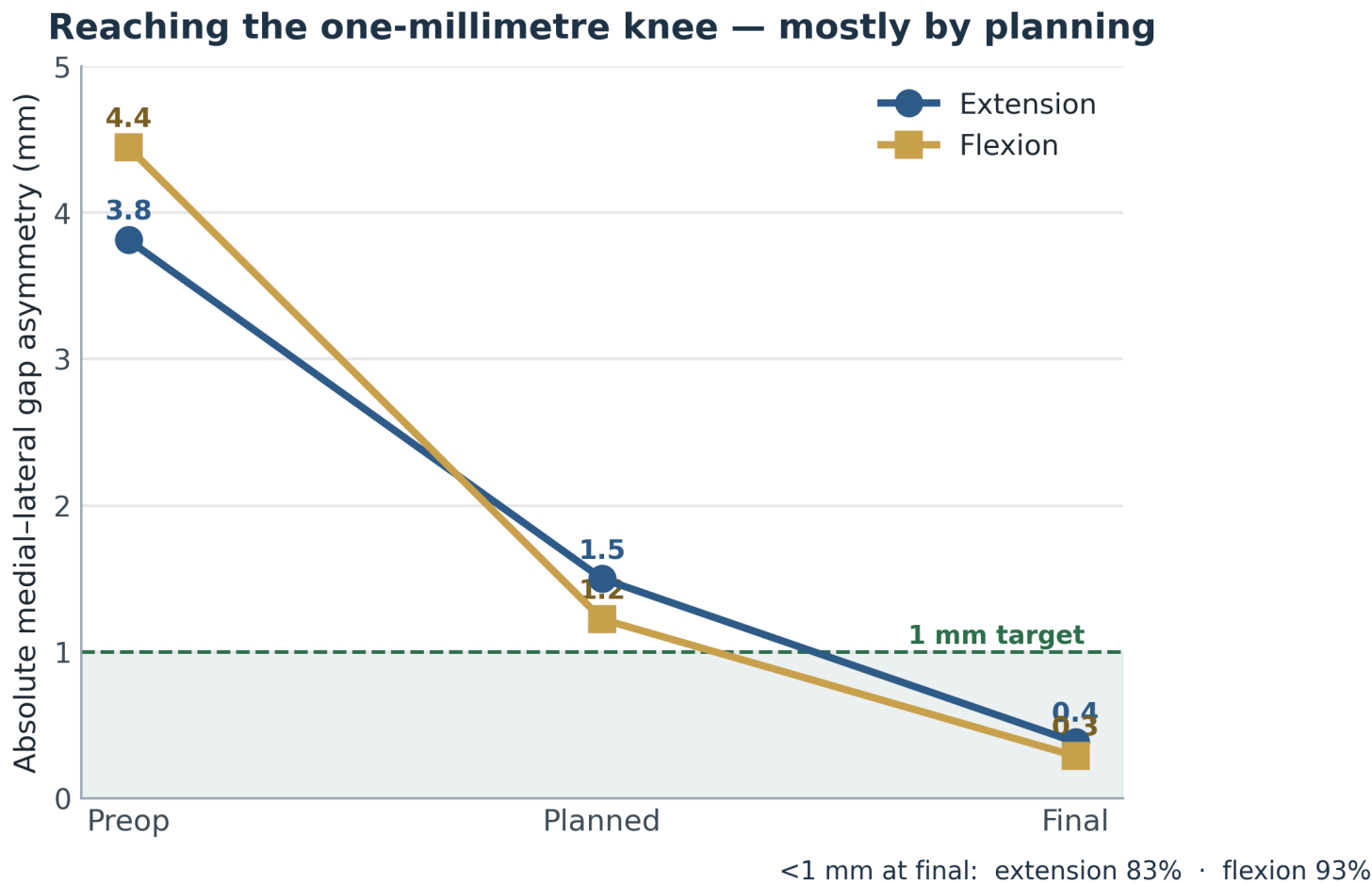
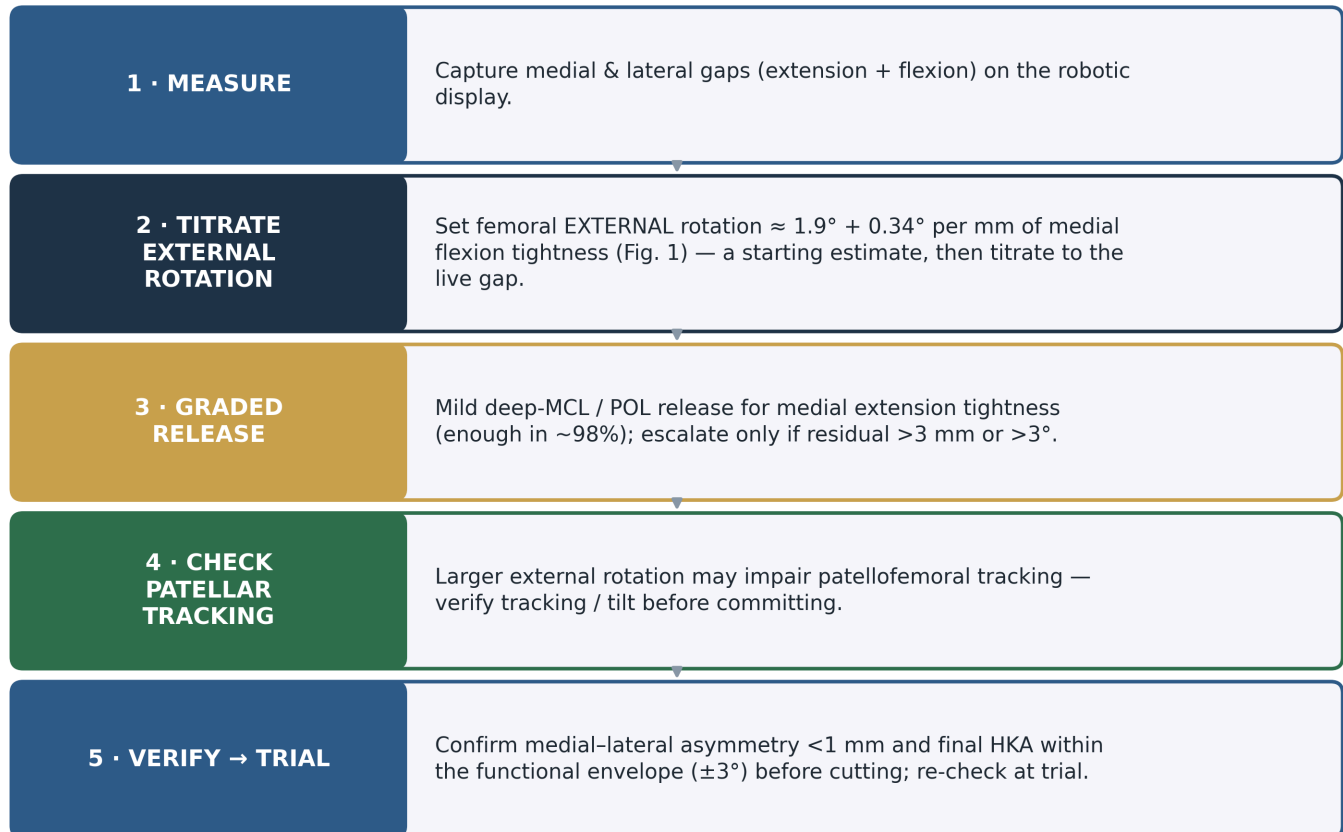


Figure 2

The one-millimetre knee. Absolute medial–lateral gap asymmetry in extension and flexion at the preoperative, planned and final states (means); asymmetry converges below the one-millimetre target (green line), reached in 83% (extension) and 93% (flexion) of knees at trialing, with most correction achieved by planning (preoperative versus final $p < 0.001$).

Varus knee balancing playbook (functional-alignment robotic TKA)



Pocket rule: rotate EXTERNALLY to the medial flexion gap ($\approx 0.34^\circ/\text{mm}$); the medial release usually stays mild.

Single-surgeon means ($R^2 = 0.26$; wide prediction band); the chart guides — it does not replace — per-knee titration and patellar-tracking assessment.

Figure 3

Varus knee balancing playbook: measure the gaps, titrate femoral rotation from the medial flexion tightness (Fig. 1), apply a mild graded medial release (escalating only for residual asymmetry >3 mm or malalignment $>3^\circ$), and verify a sub-millimetre balance at planning before cutting.