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Sehr geehrte/r Frau/Herr Prof Dr. med. Migliorini,

ich freue mich, Ihnen mitteilen zu können, dass Ihr Manuskript "Intraoperative balance in total knee arthroplasty: development and internal validation of the knee balancing score" zur Veröffentlichung in Die Orthopädie angenommen wurde.

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Herzlichen Dank für die Einreichung Ihrer Arbeit!

Mit freundlichen Grüßen,

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Intraoperative balance in total knee arthroplasty: development and internal validation of the knee balancing score

--Manuscript Draft--

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Abstract:	INTRODUCTION: Achieving accurate mediolateral soft-tissue balance is essential for stability, kinematics, and long-term outcomes in total knee arthroplasty (TKA). However, existing classification systems are often complex and lack intraoperative usability. This study introduces and internally validates the Knee Balancing Score (KBS), a simplified and reproducible method based solely on mediolateral gap asymmetry measured at full extension (when achievable) and 90° flexion using a robotic-assisted platform. METHODS: A prospective series of 285 robotic-assisted TKAs performed between 2022 and 2025 was analysed. Medial and lateral joint gaps were recorded at full extension (when achievable) and 90° flexion under standardised varus–valgus stress. The KBS was derived from the absolute gap difference (ΔGap = |L–M|, mm) and classified separately for extension (E1–E4) and flexion (F1–F4). Correlations between ΔGap and alignment parameters, including the hip–knee–ankle angle (HKA), arithmetic HKA, medial proximal tibial angle (mPTA), lateral distal femoral angle (LDFA), and joint line orientation (JLO), were calculated ($P < 0.05$). RESULTS: The mean ΔGap was 3.02 ± 2.25 mm in extension and 3.47 ± 2.63 mm in flexion ($P = 0.021$). Symmetry (E1) was observed in 21.8% of knees, while mild lateral opening (E2) occurred in 36.1%. In flexion, physiological lateral laxity (F2) was observed in 29.5%, and pathological imbalance (F3–F4) in 51.6%. Valgus morphotypes showed greater asymmetry in both planes ($P < 0.01$). ΔGap correlated inversely with HKA ($r = -0.28$ to -0.40) and mPTA ($r = -0.34$ to -0.39), confirming construct validity. CONCLUSION: The Knee Balancing Score offers a practical, physiological, and objective system to quantify intraoperative balance, transforming subjective perception into a standardised and reproducible assessment applicable in modern TKA practice.
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Intraoperative balance in total knee arthroplasty: development and internal validation of the knee balancing score

ABSTRACT

INTRODUCTION: Achieving accurate mediolateral soft-tissue balance is essential for stability, kinematics, and long-term outcomes in total knee arthroplasty (TKA). However, existing classification systems are often complex and lack intraoperative usability. This study introduces and internally validates the Knee Balancing Score (KBS), a simplified and reproducible method based solely on mediolateral gap asymmetry measured at full extension (when achievable) and 90° flexion using a robotic-assisted platform.

METHODS: A prospective series of 285 robotic-assisted TKAs performed between 2022 and 2025 was analysed. Medial and lateral joint gaps were recorded at full extension (when achievable) and 90° flexion under standardised varus–valgus stress. The KBS was derived from the absolute gap difference ($\Delta Gap = |L–M|$, mm) and classified separately for extension (E1–E4) and flexion (F1–F4). Correlations between ΔGap and alignment parameters, including the hip–knee–ankle angle (HKA), arithmetic HKA, medial proximal tibial angle (mPTA), lateral distal femoral angle (LDFA), and joint line orientation (JLO), were calculated ($P < 0.05$).

RESULTS: The mean ΔGap was 3.02 ± 2.25 mm in extension and 3.47 ± 2.63 mm in flexion ($P = 0.021$). Symmetry (E1) was observed in 21.8% of knees, while mild lateral opening (E2) occurred in 36.1%. In flexion, physiological lateral laxity (F2) was observed in 29.5%, and pathological imbalance (F3–F4) in 51.6%. Valgus morphotypes showed greater asymmetry in both planes ($P < 0.01$). ΔGap correlated inversely with HKA ($r = −0.28$ to $−0.40$) and mPTA ($r = −0.34$ to $−0.39$), confirming construct validity.

CONCLUSION: The KBS offers a practical, physiological, and objective system to quantify intraoperative balance, transforming subjective perception into a standardised and reproducible assessment applicable in modern TKA practice.

Keywords: knee balancing score, robotic-assisted total knee arthroplasty, mediolateral gap, intraoperative balance, functional alignment, joint stability, knee laxity

31 **INTRODUCTION**

32

33 Achieving a well-balanced knee remains one of the most important goals in total knee arthroplasty
34 (TKA) [1-3]. Small residual differences in soft-tissue tension can alter kinematics, compromise joint
35 stability, and influence both functional recovery and long-term implant survival [4,3]. The concept
36 of balance is therefore central to modern TKA philosophy, yet it is also one of the most debated and
37 inconsistently defined aspects of the procedure [5,6]. Despite the progress in implant design and
38 surgical technology, the way intraoperative balance is assessed still varies widely. Conventional
39 techniques often rely on the surgeon's tactile perception or on qualitative descriptors that are difficult
40 to reproduce objectively [7,8]. Various indices and balance maps have been proposed, but most are
41 complex, require additional software computation, or combine multiple variables, making them less
42 intuitive for daily clinical use [9,10]. As a result, there remains a need for a system that is simple,
43 measurable, and grounded in physiological principles. Robotic-assisted surgery has provided new
44 opportunities to objectively assess knee balance [11-13]. By allowing precise quantification of the
45 medial and lateral gaps throughout the range of motion (ROM), it offers direct insight into how the
46 soft-tissue envelope behaves during flexion and extension [14,15]. However, the abundance of
47 intraoperative data also requires an interpretative framework that can translate measurements into
48 clinically meaningful information [16].
49 The Knee Balancing Score (KBS) was developed for this purpose. It offers a straightforward
50 classification based solely on the absolute difference between the medial and lateral gaps (ΔGap =
51 $|L-M|$, mm), measured in extension (0°, when achievable) and in flexion (90°). The rationale reflects
52 native knee physiology: mediolateral symmetry in extension ensures coronal stability during stance,
53 whereas a controlled degree of lateral laxity in flexion allows for natural tibiofemoral rotation and
54 rollback.
55 The purpose of this study was to introduce and validate the KBS as a simplified, reproducible, and
56 clinically oriented system for the intraoperative assessment of mediolateral soft-tissue balance during

57 TKA. The KBS is based exclusively on the absolute mediolateral gap difference ($\Delta Gap = |L-M|$,
58 mm) measured in extension (0°, when achievable) and flexion (90°), and aims to provide an intuitive
59 classification that reflects physiological stability conditions. The study further aimed to describe the
60 distribution of KBS categories in a consecutive series of robotic-assisted TKAs and to investigate
61 their relationship with preoperative alignment parameters, including the hip–knee–ankle angle
62 (HKA), arithmetic HKA (aHKA), medial proximal tibial angle (mPTA), lateral distal femoral angle
63 (LDFA), and joint line orientation (JLO).

64 **METHODS**

65

66 **Study design**

67 All patients who underwent a robotic TKA at the Department of Orthopaedic Surgery of the
68 Eifelklinik St. Brigida in Simmerath (Germany) from 2022 to 2025 were prospectively invited to
69 participate in this investigation. The institution where the surgeries are performed is accredited by
70 "EndoCert" (EndoCert certificate, Centres of German Endoprosthetic, German Society for
71 Orthopaedics and Traumatology) [17], which supervises and certifies the quality of the surgical
72 procedures. This study was conducted in accordance with the principles of the Declaration of Helsinki
73 and its subsequent amendments. Ethics approval was granted by the North Rhine Medical Council,
74 Düsseldorf, Germany (ID 2022374).

75

76 **Eligibility criteria**

77 The inclusion criteria included: being older than 18 years, being able to provide informed consent,
78 and having symptomatic knee osteoarthritis (OA) graded stage II to IV, as defined by the Kellgren-
79 Lawrence classification. The exclusion criteria consisted of the presence of acute or chronic
80 inflammatory diseases, cancer, pregnancy or breastfeeding, uncontrolled clotting disorders, abnormal
81 blood cell counts, severe peripheral neuropathy, vascular diseases, peripheral ulcers, missing data
82 related to the study's endpoints, blood tests performed on days other than postoperative day (POD) 1
83 or 5, an inability to comply with the postoperative management protocol, or any other condition that
84 could influence study outcomes.

85

86 **Surgical technique**

87 All patients underwent identical clinical, imaging, and anaesthesia protocols before and after surgery.
88 Each patient received a single intravenous dose of 1.5 g cefuroxime at anaesthesia induction, and pain
89 was managed with a continuous femoral nerve block maintained for 48 hours. Every surgery was

90 performed using the same standard medial parapatellar approach with functional kinematic
91 alignment. All surgeries were performed using the CORI Robotic System (Smith & Nephew, UK).
92 All implant components (Smith & Nephew Legion Genesis II, posterior-stabilised, polyethylene
93 liner) were placed according to the manufacturer's guidelines. Palacos cement was used for both
94 femoral and tibial fixation. At the end of surgery, 1 g of tranexamic acid was injected intra-articularly.
95 Two drainage systems were used: a deep intra-articular drain without suction and a superficial
96 subcutaneous with suction, which remained in place for 48 hours postoperatively. Enoxaparin sodium
97 (40 mg/0.4 mL) was initiated 12 hours postoperatively and administered daily for six weeks as
98 antithrombotic prophylaxis. Standardised physiotherapy protocols were followed, with
99 physiotherapists providing care starting from the first POD. If there were no complications or other
100 medical reasons, the minimum hospital stay was five days; this was extended if patients experienced
101 postoperative setbacks, such as reduced knee mobility, difficulty walking, or trouble with
102 physiotherapy exercises. Starting on the second POD, patients participated in two daily physiotherapy
103 sessions involving 60 minutes of continuous passive motion to increase knee flexion and extension,
104 with the therapist progressively improving their ROM. Discharge was based on achieving at least 80°
105 of flexion. Ambulation began under supervision from POD-2, and stair use started on POD-4. Each
106 patient then received a tailored rehabilitation program lasting at least three weeks, either as an
107 inpatient or an outpatient. Any deviation from the planned surgical or rehabilitation approach resulted
108 in exclusion from the study
109
110 **Outcomes of interest**
111 The KBS was developed to provide a reproducible and clinically oriented framework for evaluating
112 intraoperative mediolateral balance in TKA. Table 1 summarises the core framework of the KBS and
113 defines all categories used for intraoperative interpretation throughout this study. The KBS is based
114 exclusively on the absolute mediolateral gap difference ($\Delta Gap = |L - M|$, expressed in millimetres),
115 where L and M represent the lateral and medial joint gaps, respectively. Gaps were measured under

116 standardised varus–valgus stress conditions using the robotic-assisted platform at full extension (0°,
117 or maximum achievable extension) and at 90° of flexion. Balancing measurements were obtained
118 after surgical exposure and systematic removal of osteophytes, with the patella laterally displaced to
119 ensure unobstructed joint assessment. A conventional gap balancer (Smith & Nephew) was used only
120 during the initial cases as an intraoperative cross-check, whereas all reported measurements were
121 derived from the robotic system. The platform continuously quantified, graphically rendered, and
122 automatically documented medial and lateral compartmental laxity throughout the assessment.
123 The conceptual rationale of the KBS derives from the physiological tensioning behaviour of the native
124 knee throughout the flexion–extension arc. In extension, the medial and lateral compartments are
125 expected to exhibit comparable tension to ensure coronal plane stability and correct limb alignment
126 during stance. Consequently, mediolateral symmetry was considered mandatory, and any measurable
127 medial laxity greater than 2 mm was defined as unacceptable. In this position, both compartments
128 should ideally demonstrate equivalent absolute gaps, reflecting optimal coronal equilibrium.
129 In flexion, the lateral compartment naturally becomes more compliant, facilitating external tibial
130 rotation and posterior rollback of the lateral femoral condyle. This behaviour results in a controlled
131 lateral opening relative to the medial side, typically ranging between 2 and 4 mm. Such asymmetry
132 was regarded as physiological, provided overall joint stability was maintained. Conversely, a lateral
133 opening greater than 4 mm indicates excessive laxity and potential instability, whereas medial
134 dominance with a relative medial opening exceeding 2 mm was considered pathological. In this
135 context, "symmetrical balance" in flexion (F1) refers to mediolateral symmetry under controlled
136 intraoperative testing conditions and should not be interpreted as physiological symmetry, given the
137 expected presence of lateral laxity in flexion.
138 To allow intraoperative interpretation, extension (E) and flexion (F) were classified separately
139 according to the magnitude and direction of the mediolateral gap difference. The resulting
140 classification provides an immediate understanding of balance quality and the need for potential
141 intraoperative adjustments.

Position	Category	Description	ΔGap (mm)	Direction of imbalance	Clinical interpretation
Extension (E)	E1	Symmetrical balance	≤ 2 mm	None	Ideal configuration; no correction required
	E2	Mild lateral opening	2–3 mm	Lateral	Marginally acceptable; verify tensioning
	E3	Mild medial opening	2–3 mm	Medial	Not tolerated; requires correction
	E4	Marked asymmetry	> 3 mm	Any	Not tolerated; Outside the target balancing range; requires correction
Flexion (F)	F1	Symmetrical balance	≤ 2 mm	None	Perfectly balanced configuration
	F2	Physiological lateral laxity	2–4 mm	Lateral	Normal physiological condition
	F3	Excessive lateral laxity	> 4 mm	Lateral	Not tolerated; risk of instability; requires correction
	F4	Medial laxity	> 2 mm	Medial	Not tolerated; requires correction

Table 1. KBS classification.

Over- and underconstraint were intentionally excluded from the KBS, as these conditions do not reflect intrinsic mediolateral gap behaviour and can be technically managed by adjusting femoral or tibial resections or modifying the polyethene insert thickness.

Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (version 25.0, IBM Corp., Armonk, NY, USA) and Stata (version 14, StataCorp LLC, College Station, TX, USA). Continuous variables were tested for normality using both the Shapiro–Wilk and Kolmogorov–Smirnov tests. Normally distributed data were reported as mean and standard deviation (SD), while non-normally distributed data were presented as median and interquartile range (IQR). Categorical variables were expressed as absolute numbers and percentages. Comparisons between extension and flexion ΔGap values were performed using paired t-tests or Wilcoxon signed-rank tests, depending on the distribution of the data. Between-group comparisons (varus vs valgus phenotypes) were carried out using independent samples t-tests or the Mann–Whitney U-test. Proportional differences in KBS categories were analysed using the χ^2 test or Fisher's exact test when appropriate. Correlations between intraoperative balance parameters (ΔGap in extension and flexion) and radiographic alignment measures (HKA, aHKA, mPTA, LDFA, JLO) were assessed using Pearson's or Spearman's coefficients, as

163 appropriate. The strength of correlation was interpreted according to conventional thresholds: weak
164 (r = 0.10–0.29), moderate (r = 0.30–0.49), and strong (r ≥ 0.50). A multivariate linear regression
165 model was used to identify independent predictors of mediolateral asymmetry, with ΔGap in
166 extension and flexion as dependent variables. Independent variables included age, sex, BMI, HKA,
167 mPTA, and LDFA. Multicollinearity was checked through the variance inflation factor (VIF), and
168 model fit was evaluated using adjusted R^2 values. All tests were two-tailed, and statistical significance
169 was set at $P < 0.05$.

170 **RESULTS**

171

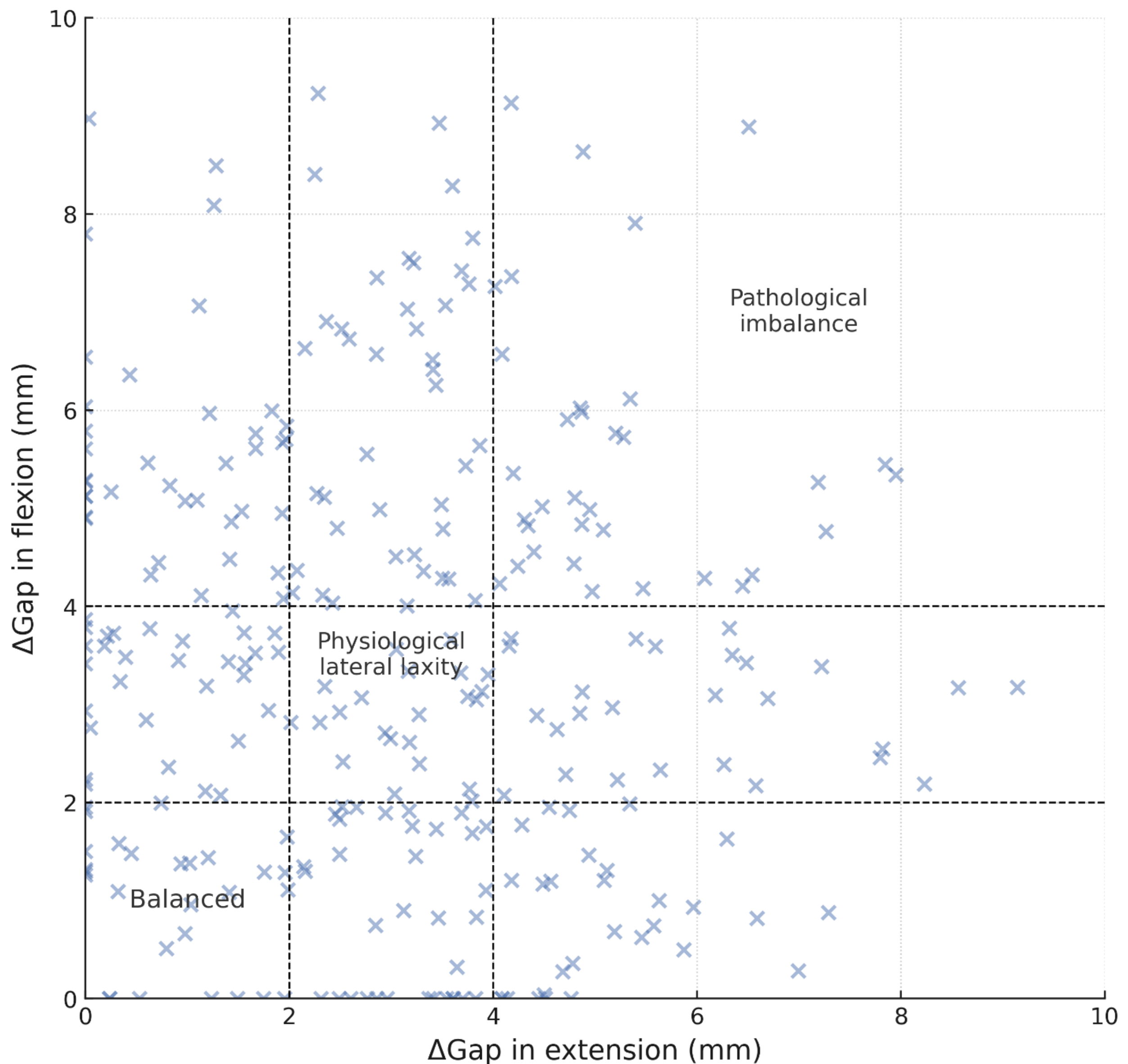
172 **Patient demographics**

173 A total of 285 consecutive patients were included in the analysis. The mean age was 67.6 ± 8.0 years
174 (range 46–87), and the mean body mass index (BMI) was 29.5 ± 4.4 kg/m² (range 19.5–43.4 kg/m²).
175 The cohort comprised 167 women (58.6%) and 118 men (41.4%), with 146 left knees (51.2%) and
176 139 right knees (48.8%). Baseline demographic variables were comparable between varus and valgus
177 phenotypes ($P > 0.05$ for age, sex distribution, and BMI).

178

179 **Intraoperative balance distribution according to the KBS**

180 In extension, the mean mediolateral ΔGap was 3.02 ± 2.25 mm (95% CI 2.75–3.29). A perfectly
181 symmetrical configuration (E1, ≤ 2 mm) was achieved in 62 knees (21.8%), while mild lateral
182 opening (E2, 2–3 mm) was observed in 103 knees (36.1%). Mild medial opening (E3, 2–3 mm) was
183 found in 61 cases (21.4%), and marked asymmetry (E4, > 3 mm) in 58 cases (20.4%). The proportion
184 of knees with acceptable balance (E1 + E2) was 57.9% (165/285), whereas 42.1% demonstrated a
185 configuration outside the target balancing range (E3 + E4). In flexion, the mean ΔGap increased to
186 3.47 ± 2.63 mm (95% CI 3.14–3.80; $P = 0.021$ vs extension, paired t-test), reflecting greater lateral
187 compliance. Symmetrical balance (F1) was observed in 54 knees (18.9%), physiological lateral laxity
188 (F2, 2–4 mm) in 84 (29.5%), excessive lateral laxity (F3, > 4 mm) in 65 (22.8%), and medial laxity
189 (F4, > 2 mm) in 82 (28.8%). Balanced or physiological configurations (F1 + F2) accounted for 48.4%
190 of all procedures, whereas the remaining 51.6% exhibited excessive or pathological imbalance (F3 +
191 F4). The ΔGap in flexion correlated strongly with ΔGap in extension ($r = 0.61$; $P < 0.001$), indicating
192 consistent intraoperative behaviour across flexion angles (Figure 1).



193

194 **Figure 1.** Scatter plot of intraoperative mediolateral ΔGap in extension and flexion according to the

195 Knee Balancing Score (KBS).

196

197 **Correlation analysis between intraoperative balance and alignment parameters**

198 Correlation analysis demonstrated moderate to strong associations between constitutional alignment

199 and intraoperative gap configuration (Table 2). Both the hip–knee–ankle angle (HKA) and arithmetic

200 HKA (aHKA) exhibited negative correlations with ΔGap in extension ($r = -0.28$, $P < 0.001$ and $r =$

201 -0.40, $P < 0.001$, respectively) and flexion ($r = -0.28$, $P < 0.001$ and $r = -0.38$, $P < 0.001$,

202 respectively). The medial proximal tibial angle (mPTA) was inversely correlated with ΔGap in both

203 extension (r = −0.34, P < 0.001) and flexion (r = −0.39, P < 0.001), whereas the lateral distal femoral
204 angle (LDFA) correlated positively, particularly in extension (r = 0.27, P = 0.002). The joint line
205 orientation angle (JLO) showed weak, non-significant associations with ΔGap in extension (r = −0.09,
206 P = 0.12) and flexion (r = −0.11, P = 0.08). Multivariate regression analysis confirmed that the
207 combination of HKA, mPTA, and LDFA explained 31.6% of the variance in ΔGap during extension
208 (adjusted $R^2 = 0.316$; P < 0.001) and 34.1% during flexion (adjusted $R^2 = 0.341$; P < 0.001).
209

Alignment parameter	r (extension)	P (extension)	r (flexion)	P (flexion)
HKA	-0.28	<0.001	-0.28	<0.001
aHKA	-0.4	<0.001	-0.38	<0.001
mPTA	-0.34	<0.001	-0.39	<0.001
LDFA	0.27	0.002	0.23	0.005
JLO	-0.09	0.12	-0.11	0.08

210
211 **Table 2.** Correlation analysis.
212
213 **Subgroup analysis**
214 When stratified by preoperative HKA, 72 knees were classified as valgus and 213 as varus. Valgus
215 knees exhibited significantly greater mediolateral asymmetry in both positions (Table 3). Extension:
216 mean ΔGap 2.23 ± 1.66 mm (varus) vs 3.43 ± 2.58 mm (valgus); mean difference 1.21 mm (95% CI
217 0.69–1.72; P = 0.0009). Flexion: mean ΔGap 2.65 ± 1.85 mm (varus) vs 4.03 ± 2.97 mm (valgus);
218 mean difference 1.38 mm (95% CI 0.80–1.97; P = 0.0013). The frequency of pathological imbalance
219 (E3–E4) in extension was 31.9% among varus and 46.9% among valgus knees (P = 0.028, χ^2 test). In
220 flexion, pathological configurations (F3–F4) were present in 36.1% of varus and 58.4% of valgus
221 cases (P = 0.011). Linear regression confirmed that valgus alignment independently predicted
222 increased ΔGap in flexion (β = 0.42; 95% CI 0.27–0.57; P < 0.001) and extension (β = 0.35; 95% CI
223 0.19–0.52; P = 0.002), even after adjusting for age, sex, and BMI.
224

Parameter	Varus	Valgus	MD (95% CI)	P value
ΔGap extension (mm)	2.23 ± 1.66	3.43 ± 2.58	1.21 (0.69–1.72)	0.0009
ΔGap flexion (mm)	2.65 ± 1.85	4.03 ± 2.97	1.38 (0.80–1.97)	0.0013
Pathological imbalance in extension (%)	31.9	46.9	-	0.028
Pathological imbalance in flexion (%)	36.1	58.4	-	0.011

225

226 **Table 3.** Subgroup analysis (MD: mean difference).

227 **DISCUSSION**

228

229 This study introduces and internally validates the KBS as a clinically oriented and physiologically
230 based method for describing intraoperative mediolateral balance in total knee arthroplasty. The score
231 was developed to translate quantitative biomechanical measurements into an immediately
232 interpretable format, relying exclusively on the absolute difference between the medial and lateral
233 gaps assessed separately in extension and flexion. The underlying rationale follows the known
234 behaviour of the native knee: mediolateral symmetry in extension contributes to coronal stability and
235 limb alignment, whereas a controlled degree of lateral laxity in flexion facilitates external tibial
236 rotation and posterior rollback of the lateral femoral condyle [18-20].
237 The intraoperative assessment of 285 robotic-assisted procedures revealed a reproducible
238 physiological pattern. In extension, complete mediolateral symmetry (E1) was present in
239 approximately one fifth of knees, whereas a mild lateral opening within the expected range (E2) was
240 the most frequent finding. In flexion, perfectly symmetrical balance (F1) was less common and a
241 limited lateral opening (F2) predominated, consistent with normal ligament behaviour. Valgus
242 morphotypes showed significantly greater ΔGap values in both positions, suggesting a higher
243 compliance of the lateral structures. Overall, these observations indicate that the KBS identifies
244 consistent balance profiles that correspond to recognised differences between varus and valgus knee
245 morphology.
246 The relationships observed between ΔGap and radiographic alignment parameters further support the
247 construct validity of the classification. Both the hip–knee–ankle angle and the medial proximal tibial
248 angle were inversely associated with ΔGap, indicating that valgus alignment tends to be accompanied
249 by greater mediolateral asymmetry. Conversely, the lateral distal femoral angle correlated positively
250 with ΔGap, highlighting the influence of distal femoral geometry on coronal plane tensioning. These
251 associations suggest that the KBS reflects physiologically meaningful characteristics of knee balance
252 rather than isolated intraoperative measurements.

253 From a methodological standpoint, the KBS was developed to remain clinically interpretable while
254 preserving analytical consistency. The use of predefined thresholds allows immediate intraoperative
255 understanding and reduces reliance on subjective judgment or composite indices. Evaluating
256 extension and flexion separately acknowledges their different biomechanical roles, coronal stability
257 in extension and functional kinematics in flexion, thereby providing a more representative description
258 of soft-tissue behaviour. The consistent distribution of balanced and pathological configurations
259 across the cohort further supports the internal coherence of the classification.
260 From a methodological perspective, formal intra- and interobserver reliability testing was not
261 performed; however, intraoperative cross-checks using a Smith & Nephew gap balancer during the
262 initial cases suggested consistent force application by the operating surgeon. Moreover, the present
263 study did not assess associations between the KBS and postoperative clinical or patient-reported
264 outcomes. Finally, as this investigation was conducted in a single centre using one robotic platform
265 and a standardised surgical workflow, the findings should be interpreted as centre- and system-
266 specific and cannot be generalised to other institutions, robotic systems, or conventional manual
267 TKA. Future studies should extend these findings by testing intra- and interobserver reliability, using
268 intraclass correlation coefficients for repeated ΔGap measurements, and by comparing the KBS with
269 other existing indices, such as the Robotic evaluation of articular laxity (REAL) classification [21].
270 The KBS and the REAL classification address intraoperative mediolateral balance from
271 complementary perspectives. While the REAL score provides a detailed phenotypic description of
272 knee laxity patterns derived from intraoperative measurements, the KBS was designed to facilitate a
273 physiologically grounded interpretation of mediolateral balance using predefined thresholds for
274 extension and flexion. Responsiveness should also be explored by analysing how the KBS changes
275 consistently following intraoperative adjustments, and predictive validity could be tested through
276 associations with postoperative outcomes and functional scores. In summary, this single-centre study,
277 based on a single robotic platform, provides only internal validation, without external validation,
278 formal reliability testing, or correlation with postoperative clinical outcomes. External validation in

279 other centres and with different robotic systems will be necessary to confirm reproducibility and
280 broader clinical applicability.
281 Clinically, the KBS provides surgeons with a simple, objective framework for interpreting
282 intraoperative balance in real time. By defining measurable thresholds that separate physiological
283 from pathological asymmetry, it links biomechanical concepts to practical surgical decision-making.
284 The score can be incorporated into robotic or navigation-assisted workflows, providing immediate
285 feedback on soft-tissue tension and supporting adjustments such as selective release or modification
286 of insert thickness. Although anatomical complexity may be anticipated from preoperative imaging,
287 surgeons have traditionally lacked a structured method to quantify the balancing requirements
288 encountered intraoperatively. Beyond its operative application, the KBS also introduces a shared
289 terminology that may facilitate comparison between studies and implant systems.

290 **CONCLUSION**

291

292 The KBS provides a clear, physiologically based, and reproducible method for quantifying
293 mediolateral balance during total knee arthroplasty. By isolating the essential information from
294 intraoperative gap measurements and defining distinct numerical thresholds for extension and
295 flexion, it transforms balance assessment from a subjective perception into an objective, standardised
296 process. The KBS bridges the gap between surgical practice and biomechanical rationale, offering
297 immediate intraoperative guidance and a reliable framework for future research on soft-tissue
298 balance, alignment, and functional outcomes in TKA.

299 **Data availability statement:**

300 The datasets generated and/or analysed during the current study are available from the authors upon

301 reasonable request.

302

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