Li et al. Journal of Orthopaedic Surgery and Research (2025) 20:281
https://doi.org/10.1186/s13018-025-05678-3

Journal of Orthopaedic Surgery and Research

RESEARCH

Open Access

Robot-assisted total knee arthroplasty is more precise than conventional total knee arthroplasty in restoring knee, but not ankle alignment: a retrospective study based on imaging data

Hongxu Li[1], Haoyang Liu[1], Yu Zhou[1], Bailiang Wang[2*] and Jinhui Ma[2*]

Abstract

Background Knee osteoarthritis often leads to varus deformity, disrupting lower limb alignment and potentially causing ankle osteoarthritis. While total knee arthroplasty (TKA) can correct knee alignment and improve ankle alignment, the impact of different alignment strategies on the ankle remains unclear. This study investigates whether robot-assisted functional alignment (RA-FA) offers advantages over conventional mechanical alignment (CM-MA) in correcting ankle alignment, addressing the paucity of evidence on the impact of alignment strategies on distal joint biomechanics.

Methods A retrospective analysis was conducted on radiographic data from 202 patients with primary knee osteoarthritis who underwent TKA. Patients were divided into two groups based on the surgical approach: CM-MA group and RA-FA group, with 101 patients in each group. Using preoperative and postoperative full-length lower limb X-rays, multiple coronal radiographic parameters of the knee and ankle joints were measured. The correlation between knee and ankle alignments was assessed. Patients were further subgrouped based on the type of knee varus deformity, and differences in alignment correction between CM-MA and RA-FA within these subgroups were analyzed.

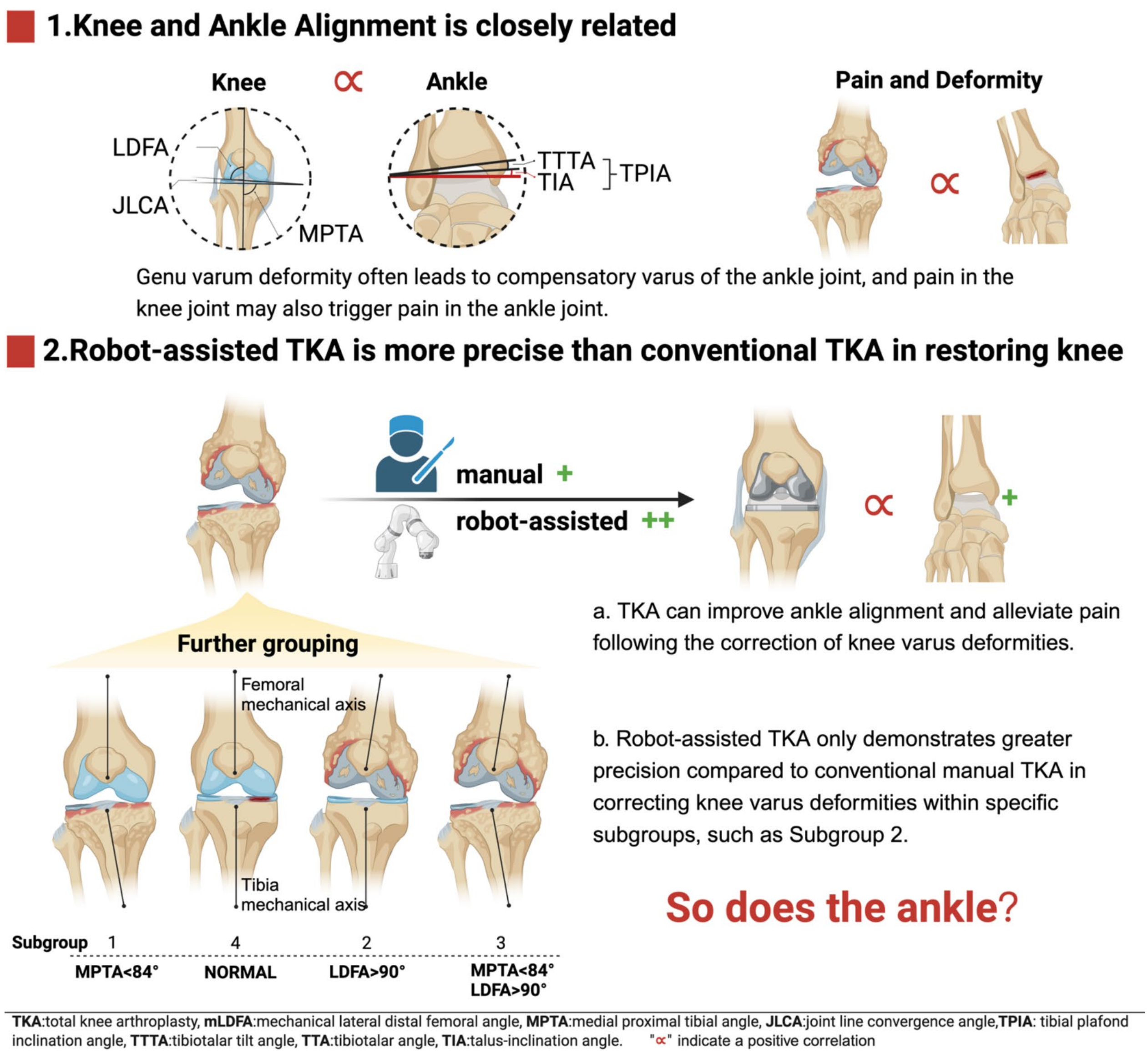
Results Preoperatively, there were no significant differences in radiographic parameters of the knee and ankle between the two groups. Postoperatively, the RA-FA group showed superior correction in HKA and mLDFA compared to the CM-MA group. However, no statistically significant differences were observed between the two groups regarding ankle alignment correction. Subgroup analysis revealed that RA-FA was more effective in correcting knee alignment in specific subgroups. Nevertheless, even in these subgroups, RA-FA did not demonstrate a significant advantage over CM-MA in correcting ankle alignment.

*Correspondence:
Bailiang Wang
wang_orthopaedic@126.com
Jinhui Ma
1402317340@qq.com

Full list of author information is available at the end of the article

Conclusion This study highlights the close relationship between knee and ankle alignments and confirms that TKA can improve ankle alignment. While RA-FA allows for more precise adjustments in femoral osteotomy and implant positioning, it does not significantly improve ankle alignment compared to CM-MA. Future studies should investigate the long-term effects of TKA on ankle alignment and evaluate whether other alignment strategies or different types of prostheses may influence the prognosis of the ankle or more distal joints such as the subtalar joint.

Graphical abstract



Keywords Total knee arthroplasty, Functional alignment, Ankle, Robot assist, Knee osteoarthritis

Introduction

Knee osteoarthritis (KOA) is a degenerative joint disease characterized by cartilage wear, with the majority of patients experiencing more severe medial cartilage damage [1, 2]. As medial cartilage destruction progresses, knee varus deformity develops, severely disrupting lower limb alignment [3]. Studies have reported that approximately 24–35% of KOA patients also suffer from ankle osteoarthritis (AOA) [4]. The onset of AOA is closely related to changes in lower limb alignment, which alter talar loading and shift the weight-bearing axis [5]. Total knee arthroplasty (TKA) is considered the ultimate solution for advanced KOA, as it effectively restores knee function and realigns the lower limb [6, 7]. Previous studies have demonstrated a strong correlation between knee and ankle alignment, with improvements in ankle alignment observed after TKA [8]. Traditional manually performed TKA typically employs the mechanical alignment (MA) strategy, aiming to restore the neutral mechanical axis of the lower limb [9]. However, Hirschmann et al. emphasized that there is significant variation in the alignment between the femoral distal and tibial proximal segments in the normal population, which leads to differing load patterns at the ankle joint [10]. The alignment strategy using MA may overly correct knee varus [10], causing the weight-bearing axis to shift medially, increasing talar tilt and calcaneal valgus, and exacerbating ankle malalignment [11, 12], ultimately resulting in postoperative ankle pain and the progression of osteoarthritis [13]. Therefore, accounting for these variations during TKA, and understanding the impact of TKA alignment strategies on ankle alignment, is crucial for maintaining long-term joint health and function.

In contrast, modern robot-assisted TKA enables the application of functional alignment (FA), a personalized alignment strategy that considers individual kinematics and functional characteristics [14]. FA seeks to restore the native joint line and alignment while maintaining overall limb function [15]. Studies have shown that compared with MA, FA can reduce the femoral resection by up to 2.3 mm and also decrease the over-resection of the medial tibial plateau [16], reduce the rate of soft tissue release [17], thereby decreasing the incidence of joint instability [16, 17] and maintaining the balance of joint spaces [18]. Furthermore, it can adjust the position of the implant in real time via the robotic system, determine the rotation of the prosthesis, and reduce the incidence of patellofemoral complications [18]. These biomechanical advantages would translate into more natural knee joint motion, a reduced risk of prosthesis revision [17], shorter hospital stays, and less postoperative pain [17].

Currently, the majority of studies on the impact of TKA on ankle joint alignment primarily employ the MA strategy [19, 20]. Although numerous investigations have compared the differences between MA and FA in restoring knee alignment and function [14], there remains a lack of studies investigating the differential biomechanical effects of these alignment strategies on distal lower limb joints, particularly the ankle. As previously noted, compared to MA, FA offers more precise [16] and individualized correctionof knee joint alignment [14]. However, the correction of ankle alignment is also influenced by the subtalar joint, surrounding ligaments, and postoperative gait. Whether the theoretical advantages of FA can translate into improved ankle alignment outcomes in the short term postoperatively remains unclear. We aims to further investigate the specific effects of various knee alignment parameters on ankle alignment and to compare the differences in coronal plane radiographic parameters of the ankle joint between MA-guided and FA-guided TKA. The findings of this study suggest that FA provides more precise femoral cuts and prosthetic placement. Therefore, we further classified knee varus deformities into distinct subgroups to assess whether FA offers superior correction of ankle alignment compared to MA in these subgroups.

Methods

TKA alignment strategies

Conventional Manual Mechanical Alignment (CM-MA) Strategy: Preoperative planning was based on anteroposterior and lateral knee radiographs, as well as standing full-length lower limb radiographs. Based on the femoral distal intramedullary osteotomy guide and the tibial proximal extramedullary osteotomy guide, the femoral distal osteotomy is set at a fixed 6-degree valgus angle. The lower limb mechanical axis and osteotomy angles are then verified to ensure that the osteotomies of the tibia and femur are perpendicular to the lower limb mechanical axis. This allows for the creation of a rectangular gap for both extension and flexion, with an assessment of whether soft tissue release is necessary to achieve the final alignment and balance.

Robot-Assisted Functional Alignment (RA-FA) Strategy: This approach required preoperative CT scanning of the affected lower limb, extending from the superior margin of the femoral head to the lowest points of the medial and lateral malleoli. The CT images were used to reconstruct the patient-specific 3D structure of the lower limb and to plan the prosthesis model, implant angles, and resection amounts preoperatively. Intraoperatively, bone registration was performed to match the patient's actual anatomical structure with the preoperative imaging. The flexion and extension gaps were assessed, and adjustments were made to the implant placement angles, positions, and resection amounts to achieve gap balance. Once knee balance was achieved, the cuts were executed, and spacers were used to test the extension and flexion gaps. When balance, tension, and stability were confirmed to be satisfactory, additional soft tissue releases were performed as needed.

All surgeries were performed by the same surgical team, and both the CM-MA and RA-FA groups utilized the Stryker Triathlon cruciate-retaining (CR) prosthesis. For the sake of simplicity, CM-MA and RA-FA will be referred to as MA and FA, respectively, in the subsequent text.

Patients enrollment

After obtaining approval from the Ethics Committee of China-Japan Friendship Hospital (Ethical Review Number: 2023-KY-089) and informed consent from the patients, we retrospectively analyzed the radiographic data of patients who underwent TKA at our hospital from January 2023 to November 2024. The inclusion criteria were: (1) primary knee osteoarthritis, (2) patients with knee varus deformity, and (3) first-time TKA on the affected side. The exclusion criteria were: (1) secondary KOA (e.g., KOA caused by autoimmune diseases such as rheumatoid arthritis), (2) patients with knee valgus deformity, (3) poor-quality full-length lower limb X-rays, (4) patients who had undergone previous surgery on the ipsilateral lower limb, (5) congenital lower limb bone dysplasia, or (6) incomplete medical records. Unlike varus knee deformities, the compensatory mechanisms of lower limb alignment in valgus knee deformities remain unclear. Moreover, robot-assisted knee replacement for valgus deformities faces significant challenges, including preoperative planning complexity, soft tissue management, and osteotomy precision [21]. Additionally, the relatively small sample size of patients with valgus deformities within our cohort limits the persuasive power of any conclusions derived from this data. Consequently, we excluded valgus deformities from our analysis. All patients underwent routine preoperative full-length anteroposterior standing lower limb X-rays during the perioperative period. These X-rays were taken in a weight-bearing standing position, with legs placed together, medial malleoli aligned, and patellae facing forward to avoid measurement errors caused by limb rotation [20], using a general-purpose X-ray machine (Philips Medical Systems, Hamburg, Germany) in our hospital.

To minimize selection bias, patients were matched preoperatively by age, BMI, and knee alignment severity (HKA, MPTA, mLDFA). Independent sample t-tests and chi-square tests confirmed no significant differences in baseline characteristics between the FA and MA groups (Table 1). A total of 223 patients participated in this study. Thirteen patients with knee valgus deformity, four with missing radiographic data, and four with secondary KOA were excluded. Ultimately, 202 patients were included in the study, consisting of 38 males and 164 females. The mean age was 68.3 ± 6.6 years (52–85 years), the mean height was 160.7 ± 6.7 cm (145–180 cm), the mean weight was 70.51 ± 11.9 kg (45–110 kg), and the mean body mass index (BMI) was 27.2 ± 3.9 kg/m² (18.1–41.0). Among them, 101 patients each underwent TKA guided by either FA or MA. The surgical time for the FA group was 25.2 min longer than that for the MA group, due to additional steps such as placing positioning pins, bone registration, and real-time adjustment of implant placement during robotic-assisted surgery.

Table 1 Basic information of the participants

	FA ($n = 101$)	MA ($n = 101$)	*P* value
Age (year)	69.08 ± 5.62	67.57 ± 7.34	0.10
Gender*			0.39
Male	16(15.8%)	22(21.8%)	
Female	85(84.2%)	79(78.2%)	
Surgical site*			0.48
left	45(44.6%)	51(50.5%)	
right	56(55.4%)	50(49.5%)	
Surgical time(min)	111.6 ± 18.6	86.4 ± 19.2	**< 0.001**
BMI	27.20 ± 3.79	27.29 ± 3.93	0.87
height(cm)	160.89 ± 6.57	160.46 ± 6.93	0.65
weight(kg)	70.55 ± 11.42	70.47 ± 12.38	0.96

*Chi-square test, the data are presented as absolute values and percentages

Independent sample t-tests and their data are presented as the mean ± standard deviation are used for the others

Radiological measurment and patient re-grouping

We imported the DICOM-format full-length lower limb X-ray images into Medical Imaging Processing Software (Wuhan United Imaging Healthcare Technology Co., Ltd.) and then two experienced orthopedic surgeons independently measured the following radiographic parameters on the full-length standing radiographs of the lower limbs (Figure 1):

1. Hip-Knee-Ankle angle (HKA): The angle between the mechanical axes of the femur and tibia.
2. Mechanical Lateral Distal Femoral Angle (mLDFA): The lateral angle formed between the distal tangent line of the femoral condyles and the mechanical axis of the femur, with a normal value of 87° ± 3°.
3. Medial Proximal Tibial Angle (MPTA): The medial angle between the tangent line of the tibial plateau and the mechanical axis of the tibia, with a normal value of 87° ± 3°.
4. Lateral Distal Tibial Angle (LDTA): The angle between the mechanical axis of the tibia and the tangent line of the subchondral plate of the distal tibia, with a normal value of 89° ± 3°.
5. Joint Line Convergence Angle (JLCA): The angle formed between the distal tangent line of the femoral condyles and the subchondral line of the tibial plateau.
6. Tibial Plafond Inclination Angle (TPIA): The angle between the subchondral plate of the distal tibia and the horizontal line.
7. Talus-Inclination Angle (TIA): The angle between the subchondral plate of the talar dome and the horizontal line, calculated as TPIA minus TTA.
8. Tibiotalar Tilt Angle (TTTA): The angle between the subchondral plate of the distal tibia and the subchondral plate of the talar dome.
9. Tibial-Talar Angle (TTA): The angle between the mechanical axis of the tibia and the talar dome.

JLCA, TPIA, TIA, and TTTA were defined as positive if the vertex of the angle was located medially, and negative

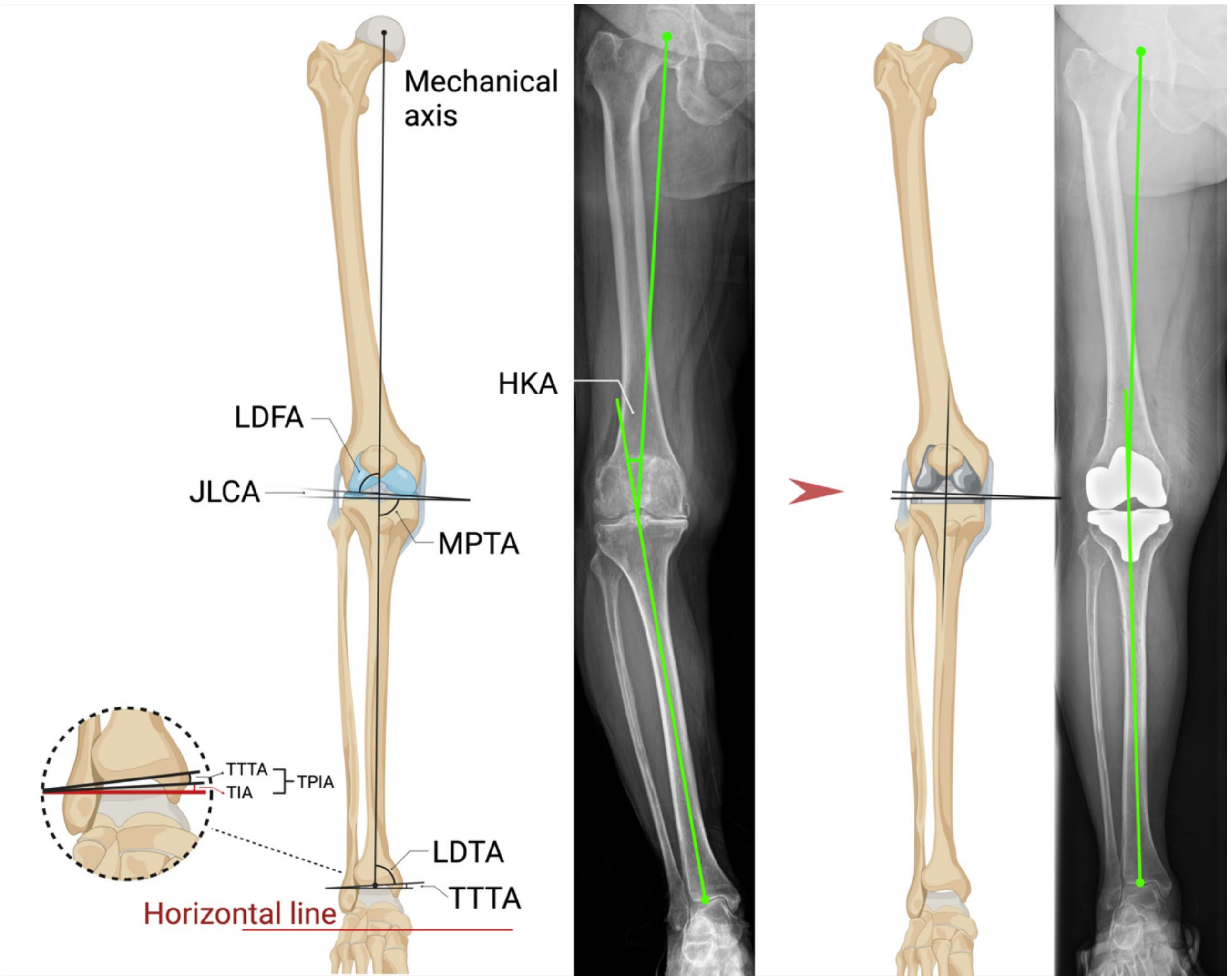


Fig. 1 Measurement methods of knee and ankle angles

if the vertex was located laterally. The Δ value refers to the postoperative value subtracted by the preoperative value. The definitions of the mechanical axes of the femur and tibia, both preoperatively and postoperatively, followed the criteria outlined in Shih et al.'s study [22].

As all patients included in this study had varus deformities, we differentiated whether the varus deformity originated from the tibia, femur, or both, based on MPTA (normal range: 84°–90°) and mLDFA (normal range: 84°–90°). Patients were categorized into four groups:

Subgroup1: Tibial Varus Deformity Group: MPTA < 84° and 84° ≤ mLDFA ≤ 90°, consisting of 33 patients (FA group: 16; MA group: 17).

Subgroup2: Femoral Varus Deformity Group: mLDFA > 90° and 84° ≤ MPTA ≤ 90°, consisting of 47 patients (FA group: 24; MA group: 23).

Subgroup3: Combined Femoral and Tibial Varus Deformity Group: mLDFA > 90° and MPTA < 84°, consisting of 49 patients (FA group: 24; MA group: 25).

Subgroup4: JLCA Varus Group: 84° ≤ mLDFA ≤ 90° and 84° ≤ MPTA ≤ 90°, consisting of 69 patients (FA group: 36; MA group: 33).

Four patients did not fit into any of the above groups and were excluded from subgroup analyses.

Statistical methods

All data were statistically analyzed using IBM SPSS Statistics version 29.0 (IBM, Armonk, NY, USA). The intraclass correlation coefficient (ICC) was employed to assess the consistency of measurements among raters for radiological parameters, and the average of two measurements was used for analysis. Quantitative data are expressed as means ± standard deviations (X ± S), while qualitative data are presented as absolute numbers and proportions. Paired t-tests were used for comparisons of radiological parameters before and after TKA surgery. Independent-sample t-tests were used when comparing the effects of mechanical and functional alignment on radiological parameters of the knee and ankle. The chi-square test

Table 2 Inter-observer consistency of radiographic parameter measurements

	HKA	MPTA	mLDFA	JLCA	TPIA	TTTA	TIA	TTA	LDTA
Pre	0.981	0.951	0.975	0.901	0.911	0.887	-	0.926	0.910
95%CI	0.963–0.990	0.925–0.973	0.952-0.984	0.870–0.936	0.899–0.925	0.846–0.910	-	0.892–0.944	0.884–0.925
Post	0.969	0.930	0.959	0.942	0.893	0.908	-	0.930	0.906
95%CI	0.941–0.979	0.892–0.961	0.949-0.980	0.919–0.966	0.859–0.933	0.878–0.918	-	0.903–0.948	0.879–0.915

Pre: preoperation, Post: postoperation

Table 3 Preoperative knee and ankle radiographic parameter values

Preoperation	FA	MA	t	*p*
Knee				
HKA	10.49 ± 5.73	10.77 ± 5.38	-0.36	0.72
MPTA	84.63 ± 2.99	84.26 ± 3.07	0.84	0.40
mLDFA	89.90 ± 2.85	89.82 ± 2.62	0.20	0.84
JLCA	5.22 ± 2.59	5.03 ± 2.74	0.52	0.60
Ankle				
TPIA	-4.07 ± 4.95	-4.14 ± 5.51	0.08	0.93
TTTA	1.29 ± 1.31	1.55 ± 1.76	-1.16	0.24
TIA	-5.36 ± 4.84	-5.68 ± 5.86	0.42	0.68
TTA	90.76 ± 4.31	90.53 ± 4.43	0.38	0.71
LDTA	87.97 ± 4.49	87.93 ± 4.18	0.08	0.94

Note: The data are presented as the mean ± standard deviation

was used for comparisons between categorical variables. Pearson correlation analysis was applied to examine the relationship between knee and ankle radiological parameters. A significance level of $\alpha = 0.05$ (two-tailed) was used, and $P < 0.05$ was considered statistically significant.

Results

Inter-observer variability analysis

ICC was classified as excellent (> 0.8), good (0.6–0.8), or poor (< 0.6) [23]. In this study, ICC for all radiographic parameters were greater than 0.8 (Table 2), indicating high consistency between the measurements of different observers. This result provides strong evidence supporting the reliability of our measurement methods, reducing potential bias caused by measurement errors.

Preoperative knee and ankle measurements and their correlation

Preoperatively, there were no significant differences in the angles of the knee and ankle joints between the FA and MA groups (Table 3). The mean varus angle of the knee joint in both groups exceeded 10°. A correlation analysis was performed, which revealed a significant correlation between preoperative knee joint angles and TPIA and TIA, and a scatter plot was generated (Fig. 2).

Postoperative knee and ankle changes and correlation of knee-ankle improvement values

Both the MA and FA groups showed significant postoperative changes in knee and ankle parameters ($p < 0.001$). In the FA group, the average HKA value improved from 10.49 preoperatively to 1.13 postoperatively, while in the MA group, it changed from 10.77 to 2.77. There was a marked difference in the degree of correction between FA and MA, with the FA group exhibiting significantly fewer outliers than the MA group. Another parameter that showed a significant difference was mLDFA, which increased from 89.89 preoperatively to 90.8 postoperatively in the FA group, while the MA group showed a larger change, from 89.82 to 92.29(Table 4).

In terms of the ankle joint, significant changes were also observed preoperatively and postoperatively. Both the FA and MA groups exhibited a shift from preoperative varus to postoperative valgus in the TPIA, with a noticeable reduction in the deformity and a clear improvement towards neutral alignment ($p < 0.001$). The TTA value also significantly decreased. However, it is important to note that when comparing between the FA and MA groups, the differences in ankle parameters were not statistically significant.

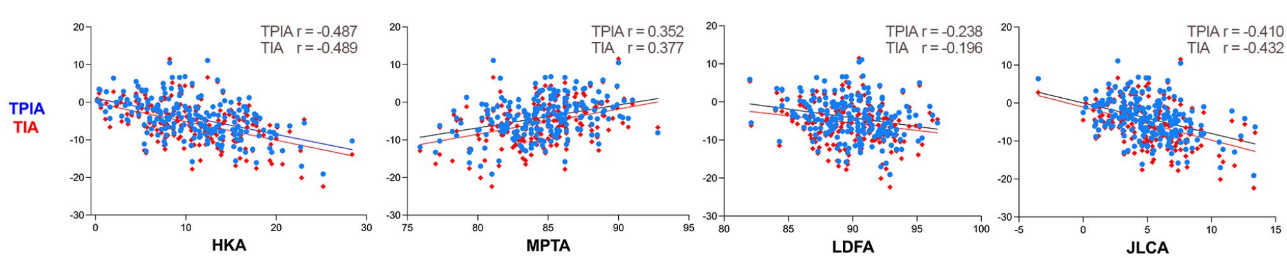


Fig. 2 The correlation of preoperative radiological parameters of the knee and ankle

Table 4 Postoperative knee and ankle radiographic parameter measurements and their Preoperative-Postoperative change values

	FA	MA	t	*p*
Knee				
HKA	1.13 ± 2.86	2.77 ± 2.85	-4.073	**0.000**
Outlier*(>3°)	24	46	10.581	**0.000**
MPTA	89.95 ± 1.83	89.53 ± 1.91	1.203	0.230
mLDFA	90.80 ± 1.81	92.29 ± 2.24	-5.212	**0.000**
JLCA	0.37 ± 0.83	0.29 ± 0.68	0.790	0.430
ΔHKA	9.36 ± 4.93	8.00 ± 5.40	1.860	0.064
ΔMPTA	5.22 ± 3.14	5.26 ± 3.15	-0.096	0.924
ΔmLDFA	0.90 ± 2.72	2.47 ± 2.73	-4.098	**0.000**
ΔJLCA	-4.85 ± 2.69	-4.74 ± 2.77	-0.291	0.771
Ankle				
TPIA	2.02 ± 4.10	1.62 ± 4.98	0.629	0.530
TTTA	0.83 ± 1.22	0.93 ± 1.59	-0.470	0.639
TIA	1.18 ± 4.24	0.69 ± 5.30	0.738	0.461
TTA	92.31 ± 4.33	92.74 ± 4.94	-0.668	0.505
LDTA	86.86 ± 4.14	86.33 ± 4.51	0.872	0.384
ΔTPIA	6.09 ± 3.98	5.75 ± 4.91	0.545	0.587
ΔTTTA	-0.46 ± 1.32	-0.62 ± 1.39	0.841	0.402
ΔTIA	6.55 ± 3.85	6.37 ± 4.94	0.292	0.770
ΔTTA	1.54 ± 3.55	2.21 ± 4.77	-1.130	0.260
ΔLDTA	-1.11 ± 3.66	-1.59 ± 4.60	0.822	0.412

*Chi-square test, independent sample t-tests are used for the others. The data are presented as the mean ± standard deviation

Regarding the correlation of knee-ankle improvement values, we found that changes in HKA and JLCA were closely correlated with the changes in TPIA and TIA (Table 5). Interestingly, the ΔmLDFA in the MA group showed a strong correlation with ΔTTA (r = -0.257), while in the FA group, no such correlation was observed (r = -0.033). To verify whether correction of knee alignment (ΔHKA) independently influences ankle alignment improvement, we performed stratified regression analysis to account for the effects of confounding factors such as preoperative height, weight, age, and knee deformity (e.g., preoperative HKA, MPTA, mLDFA, and JLCA). After including confounding factors, the results showed standardized coefficients for ΔHKA of 0.409 (TPIA) and 0.416 (TIA) ($p < 0.001$). The R-squared values for the ΔTPIA and ΔTIA regression models increased from 0.163 to 0.191 and from 0.169 to 0.194, respectively.

Table 6 Comparison of postoperative knee radiological parameters between FA and MA in each subgroup

	Sub-group	1	2	3	4
HKA	FA	1.29 ± 2.12	1.83 ± 3.23	2.50 ± 3.19	-0.24 ± 2.01
	MA	2.56 ± 2.73	3.43 ± 2.55	3.14 ± 3.36	2.37 ± 2.69
	p value	0.15	0.07	0.5	**0.00**
mLDFA	FA	90.37 ± 1.53	91.34 ± 1.79	91.33 ± 1.94	90.31 ± 1.74
	MA	91.22 ± 2.43	93.72 ± 2.10	92.32 ± 2.25	91.98 ± 1.78
	p value	0.24	**0.00**	0.11	**0.00**
MPTA	FA	89.56 ± 1.34	89.53 ± 2.16	89.23 ± 2.26	90.50 ± 1.14
	MA	88.96 ± 1.86	89.84 ± 1.82	88.98 ± 2.03	89.88 ± 1.72
	p value	0.3	0.6	0.69	0.08
JLCA	FA	0.53 ± 0.66	0.13 ± 0.80	0.53 ± 0.87	0.31 ± 0.83
	MA	0.14 ± 0.53	0.09 ± 0.57	0.48 ± 0.87	0.34 ± 0.67
	p value	0.07	0.87	0.84	0.87

Note: The data are presented as the mean ± standard deviation

Comparison of knee and ankle correction values between FA and MA in the knee varus subgroup

In each subgroup, there were no significant differences in preoperative HKA, MPTA, mLDFA, and JLCA. Postoperatively, the differences in knee alignment correction between FA and MA were primarily observed in subgroups 2 and 4 (Table 6). In these subgroups, the FA group showed a greater change in ΔHKA compared to the MA group ($p < 0.05$), with postoperative HKA values closer to neutral alignment. For mLDFA, the FA group exhibited significant improvements in both subgroup 2 ($p < 0.001$) and subgroup 4 ($p < 0.001$). In subgroup 2, the ΔmLDFA in the FA group was significantly smaller at -0.78 ± 1.84 compared to 1.90 ± 1.61 in the MA group ($p < 0.001$). The preoperative mLDFA values in subgroup 2 were all greater than 90°, indicating that postoperative mLDFA improved towards neutral alignment, while the MA group moved further away from neutral. However, in subgroup 4, there were no significant differences in the change of mLDFA between FA and MA ($p > 0.05$). Moreover, no significant differences were found in MPTA, JLCA, or their respective delta values between the FA

Table 5 Pearson correlation coefficient of changes in Knee-Ankle parameters

Pearson		ΔTPIA	ΔTTTA	ΔTIA	ΔLDTA	ΔTTA
ΔHKA	FA	**0.322****	0.041	**0.319****	0.405**	−0.439**
	MA	**0.282****	0.146	**0.239***	0.274**	−0.307**
ΔMPTA	FA	0.042	0.017	0.038	0.439**	−0.462**
	MA	0.146	0.021	0.140	0.271**	−0.267**
ΔmLDFA	FA	-0.142	-0.033	-0.135	−0.198*	0.230*
	MA	-0.097	−0.257**	-0.025	−0.201*	0.268**
ΔJLCA	FA	**−0.397****	-0.104	**−0.375****	0.020	0.008
	MA	**−0.298****	0.084	**−0.320****	-0.039	0.014

**. $p < 0.01$, *. $p < 0.05$

and MA groups across all subgroups, suggesting that the alignment strategy did not substantially impact these parameters.

As for the ankle, there were no significant differences preoperatively. In subgroup 2, which we anticipated to show differences postoperatively, the values were as follows: for TPIA, FA was 2.31 ± 3.62 and MA was 2.26 ± 4.47; for TIA, FA was 1.75 ± 3.20 and MA was 1.46 ± 4.82; and for TTTA, FA was 0.56 ± 1.34 and MA was 0.80 ± 1.02. The *p*-values for all these parameters were greater than 0.05, indicating no statistical significance. This suggests that, regardless of the advantages in knee alignment correction, there were no significant differences in ankle joint correction between the FA and MA groups (Table 7).

Table 7 Comparison of postoperative ankle radiological parameters between FA and MA in each subgroup

	Subgroup	1	2	3	4
TPIA	FA	0.98 ± 3.94	2.31 ± 3.62	1.10 ± 4.49	2.92 ± 4.19
	MA	2.12 ± 3.88	2.26 ± 4.47	-0.43 ± 6.07	2.07 ± 4.42
	p value	0.41	0.96	0.32	0.42
TIA	FA	-0.30 ± 4.78	1.75 ± 3.20	0.10 ± 4.68	2.24 ± 4.14
	MA	0.06 ± 5.01	1.46 ± 4.82	-0.93 ± 6.46	1.29 ± 4.40
	p value	0.83	0.81	0.53	0.36
TTTA	FA	1.28 ± 1.43	0.56 ± 1.34	1.01 ± 1.35	0.68 ± 0.91
	MA	2.05 ± 2.50	0.80 ± 1.02	0.50 ± 1.00	0.78 ± 1.58
	p value	0.29	0.49	0.14	0.74
LDTA	FA	88.26 ± 4.83	86.45 ± 3.80	87.13 ± 4.03	86.36 ± 4.17
	MA	87.12 ± 3.45	85.23 ± 5.21	87.70 ± 4.73	85.84 ± 3.94
	p value	0.44	0.36	0.65	0.6
TTA	FA	90.47 ± 5.56	92.99 ± 3.49	91.86 ± 4.18	92.96 ± 4.28
	MA	90.83 ± 4.79	93.97 ± 5.59	91.80 ± 4.85	93.38 ± 4.22
	p value	0.84	0.47	0.96	0.69

Note: The data are presented as the mean ± standard deviation

Discussion

This study initially explores the close relationship between the knee and ankle alignment, and compares the differences in knee alignment correction between the conventional manual MA and the robot-assisted FA strategies in patients with varus knee deformity undergoing TKA. The study further divides the varus deformity into subgroups and investigates the impact of these two methods on the coronal alignment of the ankle joint within these subgroups. Our findings suggest that the advantage of FA in knee alignment correction does not extend to the ankle joint in the short term, highlighting the need for long-term postoperative follow-up of ankle alignment and further exploration of compensatory mechanisms in more distal joints.

The close relationship between knee and ankle alignment

The ankle joint, as the pivotal connection between the foot and the leg, plays a crucial role in the alignment of the lower limb. In this study, we evaluated the radiographic parameters of the knee and ankle and found a significant negative correlation between the preoperative HKA angle and TPIA and TIA (r = -0.487 and r = -0.489, $p < 0.01$), which is consistent with previous studies' results [19, 24]. Moreover, ΔTPIA, ΔTIA, and ΔHKA are significantly correlated, indicating that the exacerbation of knee varus may lead to compensatory inversion changes in the ankle joint. The degree of correction of knee varus during TKA is closely related to the magnitude of changes in TPIA and TIA in the ankle joint, further confirming the significant impact of knee alignment on the coronal plane alignment of the ankle. From an anatomical perspective, the formation of the HKA angle is primarily influenced by the femur, tibia, and the knee joint space. To further clarify which part has the most significant impact on the ankle, we decomposed the HKA into mLDFA, MPTA, and JLCA. Regression analysis revealed that these three angles explained 96.1% of the HKA variance, and TPIA and TIA were significantly correlated with MPTA, LDFA, and JLCA, which is in agreement with previous literature [25]. This further validates the rationale for decomposing HKA and provides a theoretical basis for subgroup analysis.

Knee alignment correction before and after TKA and comparison between FA and MA groups

We first compared the knee and ankle parameters before and after TKA. Significant changes were observed in both the knee and ankle angles. Specifically, the knee varus deformity was corrected, with a slight increase in the mLDFA value postoperatively, MPTA approaching neutral alignment, and a reduction in the joint line inclination angle. These changes indicate the effectiveness of TKA in restoring normal knee alignment. However, when performing the postoperative comparison between the FA and MA groups, only HKA and mLDFA showed significant differences. Compared to the MA group, the FA group had fewer outliers in HKA values. It is important to note that the full-length X-ray films used reflect coronal plane angles and do not capture prosthetic posterior tilt or rotation, focusing solely on the varus/valgus adjustments of the prosthesis. The FA group demonstrated significantly lower mLDFA values, which were closer to neutral alignment, consistent with the findings of Lee et al. [17]. However, no significant differences were observed in other knee angles, indicating that the differences between the FA and MA alignment strategies in the coronal plane are primarily reflected in the adjustment of femoral varus/valgus alignment. The FA group demonstrated more precise adjustments in femoral osteotomy and prosthesis placement.

Based on these observations, we further divided patients with knee varus deformity into four subgroups: Subgroup 1: Predominantly tibial-sided deformities causing knee varus. Subgroup 2: Predominantly femoral-sided deformities causing knee varus. Subgroup 3: Significant deformities on both the femoral and tibial sides causing knee varus. Subgroup 4: Deformities due to abnormal joint line convergence (mainly caused by cartilage wear, with relatively mild disease). According to statistical analysis, we hypothesize that for patients with knee varus deformities primarily caused by femoral-side deformities, the FA group may offer greater advantages in knee alignment correction compared to the MA group. Although, overall, there were no significant differences in ankle parameters between the FA and MA groups, we suggest that for the specific subgroup with femoral-sided varus deformities, FA might provide more effective correction of the ankle, potentially with statistical significance. Therefore, we performed further subgroup analysis to explore these differences in detail.

In our analysis, no significant differences were observed in the preoperative HKA, MPTA, mLDFA, and JLCA values within the subgroups. However, the postoperative differences in knee alignment correction between the FA and MA groups were most notable in Subgroups 2 and 4. In these two subgroups, the FA group demonstrated a significant reduction in HKA ($p < 0.001$), with Subgroup 4 in the FA group showing smaller HKA angles, approaching neutral alignment, indicating a more effective correction of varus deformity compared to the MA group. For mLDFA, the FA group exhibited significant improvements in both Subgroup 2 ($p < 0.001$) and Subgroup 4 ($p < 0.001$), with the FA group bringing mLDFA closer to neutral alignment. Furthermore, ΔmLDFA also showed significant changes, emphasizing that the surgical intervention led to a more neutral postoperative alignment in the FA group compared to the MA group. In contrast, Subgroup 4 showed significant differences only in the postoperative mLDFA values. The ΔmLDFA for this group did not demonstrate statistically significant changes, possibly since the preoperative mLDFA values already exhibited a nonsignificant difference, which was compounded by postoperative changes (which were also not statistically significant). Therefore, the observed difference in postoperative mLDFA in Subgroup 4 likely resulted from the combination of these pre- and postoperative effects, rather than from a significant impact of the alignment strategy. For the MPTA, JLCA, and their delta values, no significant differences were found between the FA and MA groups across all subgroups, suggesting that the alignment strategy had no substantial impact on these parameters.

In summary, compared to the MA group, the FA group was able to more precisely adjust the femoral-side osteotomy and prosthetic positioning in Subgroup 2 patients, leading to more effective correction of the knee alignment.

Correction of ankle alignment after TKA and comparison of FA and MA in the knee varus subgroups

We observed that with the restoration of the knee alignment towards neutral, the ankle alignment also improved significantly. Specifically, TPIA changed from −4.10° to +1.82°, and TIA shifted from −5.52° preoperatively to +0.94° postoperatively, both improving towards neutral position. These findings are consistent with the studies by Gao and Havery et al. [8, 26], further confirming the close relationship between knee and ankle. Regression analysis indicated that confounding factors such as height, weight, and preoperative knee deformity had less than a 3% impact on ankle alignment correction, suggesting that knee alignment correction independently contributes to ankle line improvement. For every 1°correction in HKA, TPIA and TIA improved by 0.409° and 0.416°, respectively, towards neutral. Additionally, the TTTA decreased significantly from 1.42° preoperatively to 0.88° postoperatively ($p < 0.001$). However, there was no significant correlation between the correction of HKA and TTTA (r=-1.04, $p = 0.14$), but this does not affect the effectiveness of TKA in significantly improving the varus of the ankle joint and correcting the malalignment of the ankle, which is consistent with the findings of Shih et al. [22]. Nonetheless, some studies showed that for patients with genu varum correction greater than 10 degrees, TKA may exacerbate ankle mismatch [13, 19]. To explore this, we performed subgroup analysis comparing patients with knee deformities corrected by ≤10° and >10°. In patients with ≤10° correction, TTTA significantly decreased postoperatively, and the tibial-talar alignment improved. However, in patients with a >10° correction, there was no significant change in TTTA. We believe the difference in outcomes may be attributed to variations in follow-up times. In our study, radiographic analysis was performed 3 days postoperatively, while other studies were conducted at 3 months, by which time functional rehabilitation might influence ankle alignment.

Given the potential advantages of the FA strategy in knee alignment correction, as well as the close relationship between knee and ankle alignment, we anticipated that FA might demonstrate superior results in correcting ankle varus compared to MA. However, our results showed that in all subgroups of knee varus deformity, there were no significant differences between the FA and MA groups in terms of TPIA, TIA, TTTA, mLDFA, and TTA parameters, both preoperatively and postoperatively. Compared to MA, FA considers the patient's original anatomical characteristics, aligning more closely with the patient's physiological traits. It offers more precise bone cuts, prosthesis implantation, and correction of the mechanical axis [14, 27], so postoperative improvements in the ankle should theoretically be better. However, the recovery of soft tissues, such as ligaments, is delayed, and long-term compensatory valgus of the foot can cause adaptive shortening of the ligaments, joint capsules, and tendons around the ankle and subtalar joint, resulting in soft tissue tightness [28]. This chronic adaptive change means that, even after knee correction, the relevant soft tissues remain in a contracted state [28], thereby limiting ankle recovery and reducing the differences in ankle correction between alignment strategies. The recovery of stiff ligaments progresses slowly over several months postoperatively [29], which may be related to gait during postoperative daily activities [30, 31]. This indicates that, at least in the short term, FA did not show a significant advantage over MA in correcting ankle alignment. Furthermore, for patients with knee varus deformity primarily due to femoral factors, FA may more effectively restore knee alignment, thereby indirectly improving ankle positioning. However, in cases of severe concomitant ankle deformity, additional surgical intervention or more aggressive treatment strategies may be necessary, irrespective of the TKA alignment method employed.

The lack of significant correlation between preoperative knee parameters and TTTA also suggests that the impact of knee varus on the ankle joint is limited. Beyond the ankle joint, in the more distal region, the subtalar joint (a crucial part of the hindfoot) also plays a compensatory role in knee varus deformity by adjusting the hindfoot position [32, 33]. Norton et al. [34] reported a relationship between knee varus/valgus and hindfoot inversion/eversion, suggesting that knee varus is often accompanied by hindfoot eversion, and knee valgus by hindfoot inversion. A 1° varus of the knee results in a 0.5° valgus of the talus [34]. These compensations of the hindfoot aim to restore the neutral coronal plane alignment of the lower extremity. Following TKA, compensatory valgus of the hindfoot [28] and ankle improves significantly, but whether this compensation reduces or enhances the ankle's ability to compensate for knee varus deformity remains unaddressed in the literature. What is clear, however, is that the subtalar joint compensates for some cases of ankle varus deformity [35]. In contrast, compensation for ankle valgus is minimal [36] or even absent [37]. Therefore, whether in MA-TKA or FA-TKA, the compensatory role of the hindfoot on postoperative recovery of ankle compensation for knee varus is likely minimal. In severe knee varus osteoarthritis patients, excessive compensation in the subtalar joint can result in bone impingement and posterior tendonitis, leading to foot pain [38, 39]. Mullaji [32] and Hadi [40] noted that after TKA, correction of knee varus is associated with a reduction in hindfoot eversion, but a small proportion of patients still experience ankle pain postoperatively, possibly due to increased ankle joint malalignment [38]. Early TKA surgeries predominantly used the MA alignment strategy, and whether the FA alignment strategy can more effectively correct the compensatory inversion/eversion of the hindfoot and avoid ankle malalignment remains to be further investigated.

The limitations of this study include the use of only coronal plane lower limb radiographs, which can only reflect the internal and external rotational adjustments of the prosthesis, but cannot fully demonstrate the rotational and posterior tilt adjustments of the prosthesis. Therefore, it does not comprehensively reflect all the radiographic differences between FA and MA. Additionally, no clinical evaluations were performed on the knee and ankle joints, which means that the radiological differences could not be correlated with clinical outcomes. This study is limited to varus knee deformity; therefore, our findings may not be applicable to valgus knee deformity. Future research should include populations with valgus deformity to obtain more universally applicable conclusions. Knee varus deformity also leads to compensatory valgus of the subtalar joint, and the interaction mechanism between subtalar valgus and ankle valgus remains unclear. With the advent of FA alignment strategies, whether they can more precisely correct the compensatory varus and valgus in the subtalar joint requires further investigation. Lastly, only short-term postoperative radiographs were taken. Future research should include long-term follow-up, with regular assessments of both radiographic and clinical function at key postoperative time points, such as 6 months, 1 year, and 2 years. This would allow for the evaluation of dynamic changes in ankle alignment and the identification of potential delayed benefits of FA. Moreover, integrating biomechanical analyses (e.g., gait analysis, plantar pressure distribution) and patient-reported outcomes (e.g., ankle pain scores, functional scales like AOFAS) could elucidate whether subtle radiographic improvements correlate with meaningful clinical advantages.

Conclusion

Our study found that the knee-ankle alignment is closely related, and TKA can effectively improve ankle alignment when correcting knee alignment. Among the alignment strategies in TKA, FA improves knee alignment precision, especially in the femoral varus deformity group, but does not confer significant advantages over MA in restoring ankle alignment. Long-term clinical studies are needed to validate whether FA's knee advantages translate to ankle alignment improvements or reduced complications.

Abbreviations

TKA Total Knee Arthroplasty
CM-MA Conventional Manual Mechanical Alignment
RA-FA Robot-assisted Functional Alignment
KOA Knee Osteoarthritis
AOA Ankle Osteoarthritis
FA Functional Alignment
MA Mechanical Alignment
BMI Body Mass Index
ICC Intraclass Correlation Coefficient
HKA Hip-Knee-Ankle angle
mLDFA Mechanical lateral distal femoral angle
MPTA Medial proximal tibial angle
JLCA Joint line convergence angle
LDTA Lateral distal tibial angle
TPIA Tibial Plafond inclination angle
TIA Talus-inclination angle
TTA Tibiotalar angle
TTTA Tibiotalar Tilt angle
CR Cruciate-retaining
CT Computed tomography
SD Standard deviation

Acknowledgements

We are grateful to every patient and researcher who has contributed to this work.

Author contributions

HX.L: Investigation Writing– original draft, Visualization, Writing–review & editing, HY.L: Writing–review & editing, Y.Z: Data analysis, BL.W: Supervision，Funding acquisition, Resources, JH.M：Conceptualization, Project administration，Funding acquisition.

Funding

This manuscript was supported by grants from Education and teaching reform research project of Capital Medical University (2023JYY388), Elite Medical Professionals project of China-Japan Friendship Hospital (NO. ZRJY2021-TD01) and the National Natural Science Foundation of China (52373273).

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

This study has been approved by the Ethics Committee of China-Japan Friendship Hospital (Ethical Review Number: 2023-KY-089).

Consent for publication

Written informed consent for publication was obtained from the patients themselves.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Orthopaedic Surgery, Peking University China-Japan Friendship School of Clinical Medicine, Beijing 100029, China
[2]Department of Orthopaedic Surgery, Center for Osteonecrosis and Joint Preserving & Reconstruction, China-Japan Friendship Hospital, Yinghua East Street, Chaoyang District, Beijing 100029, Mainland, China

Received: 23 January 2025 / Accepted: 4 March 2025
Published online: 14 March 2025

References

1. Ramazanian T, Yan S, Rouzrokh P, Wyles CC, TJ OB, Taunton MJ, et al. Distribution and correlates of Hip-Knee-Ankle angle in early osteoarthritis and preoperative total knee arthroplasty patients. J Arthroplasty. 2022;37(6S):S170–5.
2. Liu Y, Xing Z, Wu B, Chen N, Wu T, Cai Z, et al. Association of MRI-based knee osteoarthritis structural phenotypes with short-term structural progression and subsequent total knee replacement. J Orthop Surg Res. 2024;19(1):699.
3. Yang J, Li X, Liu P, Liu X, Li L, Zhang M. The impact of patellofemoral joint diseases on functional outcomes and prosthesis survival in patients undergoing unicompartmental knee arthroplasty: a systematic review and meta-analysis. J Orthop Surg Res. 2024;19(1):840.
4. Chang CB, Jeong JH, Chang MJ, Yoon C, Song MK, Kang S-B. Concomitant ankle osteoarthritis is related to increased ankle pain and a worse clinical outcome following total knee arthroplasty. JBJS. 2018;100(9):735–41.
5. Nakasa T, Ikuta Y, Sumii J, Nekomoto A, Adachi N. High-stress distribution in the lateral region of the subtalar joint in the patient with chronic lateral ankle instability. Arch Orthop Trauma Surg. 2022;142(7):1579–87.
6. Li X, Lai J, Yang X, Xu H, Xiang S. Intra-articular injection of Vancomycin after arthrotomy closure following gentamicin-impregnated bone cementation in primary total knee arthroplasty provides a high intra-articular concentration while avoiding systemic toxicity: a prospective study. J Orthop Surg Res. 2024;19(1):856.
7. Zhao C, Liao Q, Yang D, Yang M, Xu P. Advances in perioperative pain management for total knee arthroplasty: a review of multimodal analgesic approaches. J Orthop Surg Res. 2024;19(1):843.
8. Gao F, Ma J, Sun W, Guo W, Li Z, Wang W. Radiographic assessment of knee-ankle alignment after total knee arthroplasty for varus and valgus knee osteoarthritis. Knee. 2017;24(1):107–15.
9. Oussedik S, Abdel MP, Victor J, Pagnano MW, Haddad FS. Alignment in total knee arthroplasty. Bone Joint J. 2020;102–b(3):276–9.
10. Hirschmann MT, Moser LB, Amsler F, Behrend H, Leclerq V, Hess S. Functional knee phenotypes: a novel classification for phenotyping the coronal lower limb alignment based on the native alignment in young non-osteoarthritic patients. Knee Surg Sports Traumatol Arthrosc. 2019;27(5):1394–402.
11. Chang CB, Jeong JH, Chang MJ, Yoon C, Song MK, Kang SB. Concomitant ankle osteoarthritis is related to increased ankle pain and a worse clinical outcome following total knee arthroplasty. J Bone Joint Surg Am. 2018;100(9):735–41.
12. Rühling M, Kirschbaum SM, Perka C, Graef F. Increased ankle pain after total knee arthroplasty is associated with a preoperative lateralized gait and Talar tilt, but not with ankle laxity or the range of motion of the subtalar joint. Bone Joint J. 2023;105–b(11):1159–67.
13. Jin G, Fan Y, Jiang L, Chen Z, Wang C. MAKO robot-assisted total knee arthroplasty cannot reduce the aggravation of ankle varus incongruence after Genu varus correction >/= 10 degrees: a radiographic assessment. BMC Musculoskelet Disord. 2023;24(1):492.
14. Migliorini F, Pilone M, Schäfer L, Simeone F, Bell A, Maffulli N. Functional alignment in robotic-assisted total knee arthroplasty: a systematic review. Arch Orthop Trauma Surg. 2024;144(4):1741–9.
15. Jeffrey M, Marchand P, Kouyoumdjian P, Coulomb R. Short-term functional outcomes of robotic-assisted TKA are better with functional alignment compared to adjusted mechanical alignment. SICOT J. 2024;10:2.
16. Van de Graaf VA, Chen DB, Allom RJ, Wood JA, MacDessi SJ. Functional alignment in total knee arthroplasty best achieves balanced gaps and minimal bone resections: an analysis comparing mechanical, kinematic and functional alignment strategies. Knee Surg Sports Traumatol Arthrosc. 2023;31(11):5118–27.
17. Lee JH, Kwon SC, Hwang JH, Lee JK, Kim JI. Functional alignment maximises advantages of robotic arm-assisted total knee arthroplasty with better patient-reported outcomes compared to mechanical alignment. Knee Surg Sports Traumatol Arthrosc. 2024;32(4):896–906.
18. Clark G, Steer R, Wood D. Functional alignment achieves a more balanced total knee arthroplasty than either mechanical alignment or kinematic alignment prior to soft tissue releases. Knee Surg Sports Traumatol Arthrosc. 2023;31(4):1420–6.
19. Shichman I, Ben-Ari E, Sissman E, Oakley C, Schwarzkopf R. Effect of total knee arthroplasty on coronal alignment of the ankle joint. J Arthroplasty. 2022;37(5):869–73.
20. Xie K, Han X, Jiang X, Ai S, Dai K, Yu Z, et al. The effect of varus knee deformities on the ankle alignment in patients with knee osteoarthritis. J Orthop Surg Res. 2019;14(1):134.
21. Xing P, Qu J, Feng S, Guo J, Huang T. Comparison of the efficacy of robot-assisted total knee arthroplasty in patients with knee osteoarthritis with varying severity deformity. J Orthop Surg Res. 2024;19(1):872.

22. Shih HT, Liao WJ, Tu KC, Lee CH, Tang SC, Wang SP. Poor correction capacity of preexisting ankle Valgus deformity after total knee arthroplasty. J Clin Med. 2021;10(16).
23. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J Chiropr Med. 2016;15(2):155–63.
24. Gao F, Ma J, Sun W, Guo W, Li Z, Wang W. The influence of knee malalignment on the ankle alignment in varus and valgus gonarthrosis based on radiographic measurement. Eur J Radiol. 2016;85(1):228–32.
25. Chang CB, Chung CY, Park MS, Choi JH, Kim JS, Lee KM. Aggravation of ankle Varus incongruency following total knee replacement correcting >/=10 degrees of Genu varum deformity: A radiographic assessment. J Arthroplasty. 2020;35(11):3305–10.
26. Harvey J, Eltayeb M, Moulder EH, Muir RL, Sharma HK. Compensatory mechanisms for proximal & distal joint alignment & gait in varus knee osteoarthritis treated with high tibial osteotomy: A systematic review. J Orthop. 2024;54:148–57.
27. Migliorini F, Maffulli N, Schafer L, Schneider J, Nobili AM, Kammer D, et al. Robotic-assisted total knee arthroplasty in clinical practice: protocol for a randomised controlled trial. J Orthop Surg Res. 2023;18(1):623.
28. Yoshimoto K, Noguchi M, Yamada A, Nasu Y. Compensatory function of the subtalar joint for lower extremity malalignment. Adv Orthop. 2019;2019:7656878.
29. De Vecchis M, Bowd JB, Wilson C, Whatling GM, Holt CA, Williams DE. Hip, knee and ankle kinematics improve after total knee replacement but do not return to normal. Osteoarthr Cartil. 2021;29:S184–5.
30. Hang XU, Xiaotong LI, Xinxin F, Lun AN, Yuanyuan SHI, Yu Z, et al. Biomechanical analysis of gait improvement after total knee arthroplasty. J Xuzhou Med Univ. 2021;41(9):635–9.
31. Takenaka T, Ikoma K, Ohashi S, Arai Y, Hara Y, Ueshima K, et al. Hindfoot alignment at one year after total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2016;24(8):2442–6.
32. Mullaji A, Shetty GM. Persistent hindfoot valgus causes lateral deviation of weightbearing axis after total knee arthroplasty. Clin Orthop Relat Res. 2011;469(4):1154–60.
33. Miyazaki K, Maeyama A, Matsunaga T, Ishimatsu T, Yamamoto T. Pathophysiology of abnormal compensation ability of the subtalar joint in the varus knee. J Orthop Sci. 2024;29(5):1259–64.
34. Norton AA, Callaghan JJ, Amendola A, Phisitkul P, Wongsak S, Liu SS, et al. Correlation of knee and hindfoot deformities in advanced knee OA: compensatory hindfoot alignment and where it occurs. Clin Orthop Relat Res. 2015;473(1):166–74.
35. Hayashi K, Tanaka Y, Kumai T, Sugimoto K, Takakura Y. Correlation of compensatory alignment of the subtalar joint to the progression of primary osteoarthritis of the ankle. Foot Ankle Int. 2008;29(4):400–6.
36. Wang B, Saltzman CL, Chalayon O, Barg A. Does the subtalar joint compensate for ankle malalignment in end-stage ankle arthritis? Clin Orthop Relat Res. 2015;473(1):318–25.
37. Krähenbühl N, Siegler L, Deforth M, Zwicky L, Hintermann B, Knupp M. Subtalar joint alignment in ankle osteoarthritis. Foot Ankle Surg. 2019;25(2):143–9.
38. Choudhury AK, Bansal S, Pranav J, Raja BS, Gupta T, Paul S, et al. Increased medial Talar Tilt May incite ankle pain and predispose ankle osteoarthritis after correction of severity of knee varus deformity among patients undergoing bilateral total knee arthroplasty: a prospective observation. Knee Surg Relat Res. 2024;36(1):7.
39. Stanish WD, Curwin S, Mandel S, Tendinitis. Its etiology and treatment. Oxford University Press; 2000. 31 Oct 2023.
40. Hadi H, Jabal Ameli M, Bagherifard A, Behrouzi A, Safi F, Azimi A, et al. The effect of total knee arthroplasty on hindfoot alignment in patients with severe Genu varum and Genu Valgum. Arch Bone Jt Surg. 2020;8(3):413–9.

Publisher's note