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Tomoharu Mochizuki

tommochi121710@gmail.com

Niigata University Medical and Dental Hospital

Keiichiro Someya

Niigata University Medical and Dental Hospital

Noriaki Yamamoto

Niigata Rehabilitation Hospital

Go Omori

Niigata Institute for Health and Sports Medicine

Hiroyuki Kawashima

Niigata University Medical and Dental Hospital

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Tibia-neutral functional alignment with femoral varus adjustment of up to 3° in robotic-assisted total knee arthroplasty: a preliminary prospective study using gait analysis of the bony mechanical axes

Tomoharu Mochizuki[1], Keiichiro Someya[1], Noriaki Yamamoto[2], Go Omori[3], Hiroyuki Kawashima[1]

[1]Department of Orthopaedic Surgery, Niigata University Medical and Dental Hospital, 1-757 Asahimachi-dori, Chuo-ku, Niigata City, Niigata 951-8510, Japan

[2]Department of Orthopedic Surgery, Niigata Rehabilitation Hospital, 761 Kizaki, Kita-ku, Niigata City, Niigata 950-3304, Japan

[3]Niigata Institute for Health and Sports Medicine, Inside Denka Big Swan Stadium, 67-12 Seigoro, Chuo-ku, Niigata City, Niigata 950-0933, Japan

Corresponding author: Tomoharu Mochizuki, Department of Orthopaedic Surgery, Niigata University Medical and Dental Hospital, 1-757 Asahimachi-dori, Chuo-ku, Niigata City, Niigata 951-8510, Japan. E-mail: tommochi121710@gmail.com

Abstract

Background: Robotic-assisted total knee arthroplasty allows bone cuts to be adjusted in 1° increments, but how much adjustment is acceptable remains unclear. Our standard strategy is a tibia-neutral functional alignment: the tibial component is fixed perpendicular to the mechanical axis, and only the coronal alignment of the femoral component is adjusted, within 3° of varus, to balance the knee in varus–valgus, extension and flexion. The aim of this study was to evaluate this strategy using gait analysis of the bony mechanical axes.

Methods: Twelve knees in 10 women with varus knee osteoarthritis who underwent robotic-assisted total knee arthroplasty with this strategy were studied. Two-dimensional to three-dimensional registration of biplanar full-length radiographs and computed tomography was combined with three-dimensional motion analysis to compare the mechanical axes of the femur and tibia, the dynamic weight-bearing line, and knee

moment during gait before and after surgery. Paired t-tests or Wilcoxon signed-rank tests (according to normality), two-way repeated-measures analysis of variance, and Pearson or Spearman correlation coefficients were used.

Results: The femoral component was placed in a mean of 1.8° of varus and the tibial component at a mean of 0.0°. Joint line obliquity was within the neutral range in 11 of 12 knees. The waveforms of the tibial mechanical axis and the dynamic weight-bearing line were similar in shape to those before surgery, and the change in the varus direction decreased. The peak knee adduction moment decreased from 4.0 to 2.8 %BW·Ht ($p < 0.001$). However, the greater the varus angle of the femoral component, the larger the knee adduction moment ($r = -0.772$).

Conclusions: Femoral adjustment within 3° of varus appears appropriate in terms of joint line obliquity and gait kinematics. However, femoral varus increases the knee adduction moment; varus should therefore be limited to the amount required for balance, with 3° as the upper limit.

Trial registration: Not applicable (prospective observational study: IRB number 2020-0448).

Keywords: Robotic-assisted total knee arthroplasty, Functional alignment, CPAK classification, Joint line obliquity, Gait analysis, Bony mechanical axis, Dynamic weight-bearing line, Knee adduction moment

Background

In total knee arthroplasty (TKA), mechanical alignment (MA), in which both the femur and tibia are cut perpendicular to their mechanical axes, has long been the standard. However, about one in five patients remains dissatisfied after TKA performed with MA [1]. Moreover, a certain proportion of healthy adults have constitutional varus [2], which has raised questions about correcting every knee to neutral alignment.

Kinematic alignment (KA), which restores each patient's native joint surfaces, was therefore proposed [3]. With the spread of robotic-assisted TKA (rTKA), functional alignment (FA) has emerged, in which bone cuts are adjusted in 1° increments to balance the gaps and the resulting alignment follows from this balancing [4]. The coronal plane alignment of the knee (CPAK) classification, which divides knees into nine phenotypes according to limb alignment and joint line obliquity, has also been proposed [5], providing a common basis for discussing individualized alignment strategies.

However, how far bone cuts can be adjusted remains unclear. Varus placement of the tibial component, particularly in combination with obesity, can lead to medial tibial collapse and loosening [6, 7]. In postmenopausal women with varus knees, low bone mineral density is associated with varus deformity [8], and advanced varus knee osteoarthritis in Japanese patients shows greater varus than reported in Western populations [9]. KA and conventional FA, which accept varus on the tibial side, should therefore be applied to Japanese patients with caution.

Our standard strategy for rTKA is to keep the tibia perpendicular to its mechanical axis and to adjust only the coronal alignment of the femur, within 3° of varus, to balance the knee in varus–valgus, extension and flexion. We call this tibia-neutral functional alignment (TN-FA). The aim of this study was to describe the concept and technique of TN-FA and to evaluate its validity and limitations by comparing gait analysis of the bony mechanical axes before and after surgery. We tested three hypotheses: (1) TN-FA keeps joint line obliquity within the neutral range of the CPAK classification while the tibia remains neutral; (2) after surgery, the pattern of tibial motion during gait is preserved, and varus motion and the knee adduction moment decrease; and (3) the greater the varus angle of the femoral component, the larger the postoperative knee adduction moment.

Methods

Study design and participants

This was a single-center prospective observational study comparing the same knees before and after surgery. From the knee surgery cases registered in our gait analysis database, we included 12 knees in 10 women (two bilateral cases) who underwent rTKA with TN-FA for varus knee osteoarthritis and had gait analysis both before and after surgery. Four knees treated with conventional (manual) TKA and three knees treated with unicompartmental knee arthroplasty, all analyzed during the same period, were excluded. Before surgery, mean age was 72.1 ± 6.3 years (range, 59–80 years), height 151.2 ± 4.0 cm, body weight 59.2 ± 9.9 kg, and body mass index (BMI) 25.8 ± 3.6 kg/m^2. The median interval between the preoperative and postoperative measurements was 12.9 months (range, 4.1–16.8 months). Clinical outcomes were assessed with the Japanese Knee Osteoarthritis Measure (JKOM) and its pain visual analogue scale (VAS).

Surgical technique (TN-FA)

The key principle of this strategy is to leave the tibia neutral and to balance the knee with the femur (Fig. 1, Table 1). The tibial component is fixed at 0° of varus–valgus, and only the coronal alignment of the femoral component is adjusted, within 3° of varus, to balance the knee in varus–valgus, extension and flexion. Femoral varus is not residual deformity that could not be corrected; it is an angle deliberately chosen to achieve good balance, and limb alignment follows from it. This approach is based on the concept of constitutional varus [2] and on the report that slight undercorrection of varus knees yields better clinical outcomes [10]. Because we found no established name or published description of this technique, we named it TN-FA to make the handling of the tibia explicit.

We leave the tibia neutral because varus placement of the tibial component is a risk factor for loosening [6, 7], and because reproducing the native joint surface on the tibial side in Japanese knees, which have large varus deformity [9], would require substantial tibial varus. We limit femoral varus to 3° for two reasons. First, long-term outcomes are good when limb alignment is within 3° of neutral [11]. Second, joint line obliquity (JLO) stays within the neutral range. In the CPAK classification, JLO is the sum of the medial proximal tibial angle (MPTA) and the lateral distal femoral angle (LDFA); values below 177° are classified as apex distal, 177–183° as neutral, and above 183° as apex proximal [5]. The JOURNEY II bi-cruciate stabilized (BCS) prosthesis (Smith & Nephew) that we use is designed to reproduce the native joint surface, which is in about 3° of varus, and the articular surface of its femoral component incorporates about 3° of valgus [12]. Within this range of femoral varus, the articular surface is unlikely to become abnormally inclined. If balance cannot be achieved with 3° of varus, soft-tissue release is added.

The procedure is as follows. An MA plan is made from preoperative computed tomography (CT) and entered into the robotic system (NAVIO, Smith & Nephew). Varus–valgus balance is assessed intraoperatively in extension and flexion. The tibial plan is kept unchanged (0° of varus–valgus and 3° of posterior slope), and only femoral varus–valgus, flexion and rotation are adjusted within the ranges shown in Table 2 before the bone cuts are made. Femoral rotation is set toward external rotation to avoid patellar subluxation.

Three-dimensional lower-limb alignment (static standing)

A three-dimensional lower-limb alignment assessment system (KneeCAS, LEXI) was used [13, 14]. Full-length radiographs were taken in the standing position on a turntable from anteroposterior (0°) and oblique

(60°) directions (FCR CAPSULA, Fujifilm). Three-dimensional bone models created from CT were matched to the bone contours on the radiographs by two-dimensional to three-dimensional (2D-3D) registration to determine the three-dimensional position of the bones under weight-bearing conditions (Fig. 2). The registration error is within 0.6° in rotation and 0.5 mm in translation [13].

Bone coordinate systems were defined according to Sato et al. [14]. For the tibia, the z-axis was the line connecting the midpoint of the intercondylar eminence and the center of the talar dome, and the y-axis was the perpendicular from the center of the posterior cruciate ligament insertion to the z-axis. For the femur, the x-axis was the line connecting the centers of spheres fitted to the medial and lateral posterior condyles (geometric center axis), and the z-axis was the line perpendicular to the x-axis in the plane containing its midpoint and the center of the femoral head.

The femorotibial angle (FTA) was the angle between the anatomical axes, each obtained by least-squares fitting of the cross-sectional centroids of the shaft (10 sections for the femur and 12 for the tibia), projected onto the coronal plane of the femoral coordinate system [15, 16]. The hip-knee-ankle angle (HKA), femoral mechanical angle (FMA) and tibial mechanical angle (TMA) were defined according to Hirschmann et al. [17]. TMA corresponds to MPTA and 180° − FMA to LDFA; the arithmetic HKA (aHKA) was calculated as MPTA − LDFA and JLO as MPTA + LDFA for the CPAK classification [5]. The angle between the distal femoral and proximal tibial articular surfaces was defined as the joint line convergence angle (JLCA). Component positions were determined by 3D-3D matching of implant models to postoperative CT and expressed as angles relative to the bone coordinate systems [14].

Gait analysis of the bony mechanical axes

We used our method, which combines three-dimensional motion analysis with KneeCAS and three-dimensional bone models created from CT data to estimate the motion of the bones themselves during gait [15, 16, 18]. Of the 34 reflective markers, 12 on the thigh and 10 on the shank contained steel balls so that their positions could be detected on radiographs. Thigh markers were placed on the greater trochanter, the medial and lateral epicondyles and around the femoral shaft; shank markers were placed on the medial and lateral tibial condyles, the medial and lateral malleoli, the fibular head, the tibial tuberosity and around the tibial shaft. Level walking along a 12.0 m flat lane at a self-selected speed was recorded with an optical motion capture system (VICON 612, Vicon Motion Systems, Oxford, UK) and marker trajectories were

smoothed with a fourth-order zero-lag Butterworth filter (6 Hz). The ground reaction force produced during walking was measured at 240 Hz by using six force plates (Kistler, Winterthur, Switzerland) set on the ground (Fig. 3). Biplanar standing radiographs were taken with the markers in place, and the position of each marker relative to the bones was determined with KneeCAS. The bone position at each time point was estimated by finding, with weighted least squares, the coordinate transformation that minimized the discrepancy between the marker positions in the bone coordinate system and those during gait (Eq. 1) [18]. A weighting factor was set for each marker to reduce errors caused by skin motion.

$$J[T_{FW}(t)] = \min \Sigma_{i=1}^{12} \| w_i (p_{F,i} \cdot T_{FW}(t) - q_{WT,i}(t)) \|^2 \quad (Eq.\ 1)$$

where $p_{F,i}$ is the position of the i-th marker in the femoral coordinate system, $q_{WT,i}(t)$ is the marker position at time t, $T_{FW}(t)$ is the transformation from the femoral coordinate system to the floor coordinate system, and w_i is the weighting factor. The tibia was treated in the same way. The stance phase, from initial contact to toe-off, was normalized to 100% and divided into loading response (0–20%), mid-stance (20–50%), terminal stance (50–83%) and pre-swing (83–100%) [16, 19].

Dynamic parameters

Inclination of the tibial and femoral mechanical axes relative to the ground: the angle between each mechanical axis and the vertical in the coronal plane of the floor coordinate system (y-axis, direction of progression; z-axis, vertical), with lateral inclination positive [16]. Hereafter these are referred to as the tibial axis and the femoral axis.

Dynamic alignment: the angle between the femoral and tibial mechanical axes in the coronal plane of the floor coordinate system (varus negative) [16].

Dynamic weight-bearing line (dynamic WBL): the point at which the load axis of the knee, connecting the center of the femoral head and the center of the distal tibial articular surface, passes through the proximal tibial articular surface during gait [18]. The center of the articular surface was defined as 0% and the medial and lateral edges as 100%, with medial positive [20]. The static standing WBL was defined in the same way.

Knee adduction moment (KAM): the external knee moment obtained by inverse dynamics, normalized to body weight and height (%BW·Ht). The peak values during stance and during loading response were evaluated [15].

Each parameter was evaluated in two ways: location, the absolute value, and translation, the change from initial contact.

Statistical analysis

Normality was assessed with the Shapiro–Wilk test. Preoperative and postoperative values were compared with the paired t-test when the differences were normally distributed and with the Wilcoxon signed-rank test otherwise. Stance-phase waveforms were compared with two-way repeated-measures analysis of variance (ANOVA) with condition (preoperative, postoperative) and time as factors. The main effect of condition was interpreted as a difference in the level of the waveform, and the condition × time interaction as a difference in its shape; the Greenhouse–Geisser correction was applied to the interaction. The whole stance phase and the loading response were analyzed. Correlations were assessed with Pearson's correlation coefficient when both variables were normally distributed and with Spearman's rank correlation coefficient otherwise. Significance was set at 5%. Because this was a preliminary study, no a priori sample size calculation was performed. Analyses were performed in IBM SPSS Statistics (version 27; IBM Corp., Armonk, NY, USA).

Use of a large language model

A large language model (Claude, Anthropic) was used to assist in writing the analysis code, drafting the manuscript, editing the Japanese text, translating the manuscript into English and checking the bibliographic details of the references. The authors verified all text and references against the original sources and take full responsibility for the content.

Results

Clinical outcomes and gait conditions

JKOM improved from 56.6 to 20.2 points and VAS from 6.7 to 1.0; walking speed increased from 0.84 to 1.05 m/s and stride length from 0.96 to 1.09 m (Table 3). Body weight and BMI did not change.

Component positions

The femoral component was placed in a mean of 1.8° of varus (range, 3.1° varus to 0.9° valgus) and the tibial component at a mean of 0.0° (range, 1.8° varus to 1.4° valgus) (Table 4). Two knees slightly exceeded 3° of varus (3.04° and 3.10°), both within measurement error.

Static alignment and CPAK classification

TMA changed from 82.5° to 90.0°, making the tibial articular surface perpendicular to the mechanical axis. FMA changed from 90.0° to 88.3°, which was not significant. HKA changed from 10.8° to 2.7° of varus (Table 5). JLO changed from 172.5° to 181.8°. Before surgery, nine knees were CPAK type I and three were type IV; after surgery, six were type IV, four type V, one type VI and one type VIII (Fig. 4). No knee became apex distal after surgery, and only one knee, in which the femoral component was placed in 3.0° of varus, became apex proximal (184.4°).

Gait kinematics

The locations of the tibial axis, femoral axis, dynamic alignment and dynamic WBL all changed significantly after surgery (main effect of condition, $p < 0.001$ for all; Fig. 5, Tables 6 and 7). The shapes of the waveforms (interaction) did not differ between before and after surgery for the tibial axis ($p = 0.215$) or the dynamic WBL ($p = 0.165$); the tibial axis inclined laterally during loading response and then reached a plateau both before and after surgery. In contrast, the shapes differed for the femoral axis ($p = 0.011$) and dynamic alignment ($p = 0.049$). The differences were seen mainly at the end of stance (after about 90%), where the knee moved markedly in the varus direction after surgery (Fig. 5D, F).

Over the whole stance phase, translation decreased after surgery for dynamic alignment (mean, −2.7° to −1.9°; $p = 0.004$) and dynamic WBL (22.3% to 14.1%; $p = 0.013$); the tibial axis tended to decrease ($p = 0.053$), and the femoral axis did not change ($p = 0.969$). During loading response, translation decreased after surgery for the tibial axis (1.8° to 1.1°; $p = 0.001$), dynamic alignment (−1.6° to −0.5°; $p < 0.001$) and dynamic WBL (14.7% to 5.3%; $p = 0.004$).

KAM and femoral component position

The peak KAM decreased from 4.0 ± 1.1 to 2.8 ± 0.8 %BW·Ht both during stance and during loading response ($p < 0.001$ for both; Fig. 6C). After surgery, the more varus the femoral component, the more

varus the dynamic alignment (r = 0.646, p = 0.023) and the larger the peak KAM (stance, r = −0.772, p = 0.003; loading response, r = −0.750, p = 0.005) (Fig. 6A, B; Table 8). Postoperative JLCA correlated with dynamic alignment (r = −0.813, p = 0.001) and KAM (r = 0.639, p = 0.025), and HKA correlated with dynamic alignment (r = −0.663, p = 0.019). Tibial component position, FTA and static standing WBL did not correlate with postoperative gait kinematics or KAM.

Before surgery, FTA, static standing WBL and HKA correlated with the locations of the femoral axis, dynamic alignment and dynamic WBL (e.g., FTA and dynamic alignment, r = −0.768, p = 0.004), and JLCA correlated strongly with KAM (r = 0.859, p < 0.001; Table 9).

Discussion

The three hypotheses were largely supported. Regarding hypothesis 1, the tibial component was placed at a mean of 0.0°, and JLO was within the neutral range in 11 of 12 knees. Regarding hypothesis 2, the absolute values of the tibial axis and dynamic WBL changed after surgery, but the shapes of their waveforms were preserved, and both the change in the varus direction and KAM decreased. In contrast, the waveforms of the femoral axis and dynamic alignment differed in shape from those before surgery at the end of stance. Regarding hypothesis 3, the greater the femoral varus angle, the larger the KAM, which supports the 3° upper limit.

A neutral tibia with JLO kept within the neutral range

KA and conventional FA accept varus placement of the tibial component to preserve the native joint surface [3, 4]. However, tibial component varus greater than 3° causes medial tibial collapse in patients with high BMI [6]. In a study of about 6,000 knees, the failure rate was 8.7% when tibial varus was combined with femoral valgus, compared with 0.2% when both components were neutral [7]. To avoid this risk, TN-FA keeps the tibia perpendicular to its mechanical axis, and the tibial component was placed within 2° of neutral in all knees.

Keeping the tibia neutral did not compromise JLO. In 500 Japanese knees with osteoarthritis, CPAK type I was the most common (53.8%), and no knee was apex proximal (types VII–IX) [21]. MA changes JLO substantially: in 700 knees after MA TKA, 60% became type V, and apex proximal knees increased from 0.7% to 11.1% [22]. In 284 Japanese knees after MA TKA, postoperative apex proximal JLO was an

independent predictor of poor clinical outcome [23]. In contrast, robotic FA changes JLO less [24]. Because TN-FA sets the MPTA at 90°, JLO at the level of the bone cuts does not exceed 183° as long as femoral varus is within 3°. Furthermore, the articular surface of the JOURNEY II BCS femoral component incorporates about 3° of valgus. Even when the femur is cut in x° of varus, the LDFA of the articular surface is therefore about 87° + x and the MPTA of the insert about 87°, so the articular surface remains close to the apex distal range that is common in Japanese knees. In this study, the mean postoperative JLO was 181.8°, and only one knee, with the femoral component in 3.0° of varus, exceeded the neutral range (184.4°).

Preserved tibial motion with reduced varus change and KAM

The pattern in which the tibial mechanical axis inclines laterally during loading response and then reaches a plateau is common to healthy adults [25] and knees with osteoarthritis [16], and probably reflects the alignment of the medial tibial articular surface parallel to the ground under weight-bearing conditions [26]. Gait is a whole-body movement involving shifts of the center of mass to maintain balance under gravity [19], which may explain why changing the articular surface did not substantially alter tibial motion. In this study, the change in the varus direction was smaller after surgery than before, particularly during loading response. The abrupt varus change in early loading seen in varus knees appears to have been reduced by surgery, and walking ability recovered without substantially altering tibial motion.

KAM also decreased by about 30% from before surgery. After MA TKA, KAM has been reported to be 85% of the preoperative value at 6 months and 94% at 1 year [27]. KAM closely reflects medial knee loading; in vivo measurements with instrumented implants showed that the proportion of medial load increased by about 5% per 1° of varus [28]. Medial load correlated strongly with KAM ($R^2 = 0.85$) but hardly at all with the dynamic joint line orientation during gait [29].

In contrast, the differences in the waveforms of the femoral mechanical axis and dynamic alignment appeared mainly just before toe-off, and may reflect the apparent inclination of the bone axes with knee flexion or varus–valgus motion of the implant in flexion.

Femoral component varus and KAM—the meaning of the 3° upper limit

Although TN-FA places varus on the femoral side, femoral varus is not unlimited. Lee et al. reported that, in knees with limb alignment more than 3° varus, femoral component varus was the main cause and was a risk factor for aseptic tibial loosening (odds ratio, 14.0) [30]. In individual knees after surgery in this study, the more varus the femoral component, the larger the KAM. This is consistent with the report that knees with residual varus after TKA had a 19% larger KAM than neutral knees without any functional benefit [31]. In KA, KAM is smaller than in MA even with slight limb varus [32, 33], partly because the tibial articular surface is also inclined in varus and becomes nearly parallel to the ground during stance. In TN-FA, because the tibia is perpendicular to its mechanical axis, varus added on the femoral side translates directly into limb varus and is reflected in KAM. Together with the report that femoral component varus is a risk factor for tibial loosening [30], a reasonable safety margin for TN-FA is to use only as much varus as needed for balance and never more than 3°; TN-FA therefore presupposes strict adherence to this upper limit. Neutral alignment itself did not improve 15-year survival in one study [34], and the long-term effect of a slight increase in KAM remains to be determined.

Limitations

First, the sample was small (12 knees in 10 women) and included two bilateral cases, both knees of which were treated as independent samples. Second, the interval between measurements varied (4–17 months), and the results are short term. Third, there was no comparison group treated with another strategy such as MA or KA. Fourth, only one robotic system and one implant were used, and JLO of the articular surface was estimated from the design values of the implant. Fifth, KAM is a surrogate for medial knee loading, and its relationship with loosening was not examined.

Conclusions

In rTKA with TN-FA, in which the tibia is kept perpendicular to its mechanical axis and only the coronal alignment of the femur is adjusted within 3° of varus to balance the knee, the femoral component was placed in a mean of 1.8° of varus and the tibial component at 0.0°, and JLO was within the neutral range of the CPAK classification in 11 of 12 knees. The waveforms of the tibial axis and dynamic WBL were similar in shape to those before surgery, and the change in the varus direction and KAM decreased.

However, because the varus angle of the femoral component affects dynamic alignment and KAM, femoral varus should be limited to the amount needed for balance and kept within 3°.

List of abbreviations

aHKA	arithmetic hip-knee-ankle angle (MPTA − LDFA)
ANOVA	analysis of variance
BCS	bi-cruciate stabilized
BMI	body mass index
CPAK	coronal plane alignment of the knee
CT	computed tomography
FA	functional alignment
FMA	femoral mechanical angle
FTA	femorotibial angle
HKA	hip-knee-ankle angle
JKOM	Japanese Knee Osteoarthritis Measure
JLCA	joint line convergence angle
JLO	joint line obliquity
KA	kinematic alignment
KAM	knee adduction moment
LDFA	lateral distal femoral angle
MA	mechanical alignment
MCT	plane fitted to the medial tibial articular surface (Table 9)
MPTA	medial proximal tibial angle
ROM	range of motion
rTKA	robotic-assisted total knee arthroplasty
SD	standard deviation
SEA	surgical epicondylar axis

TKA	total knee arthroplasty
TMA	tibial mechanical angle
TN-FA	tibia-neutral functional alignment
VAS	visual analogue scale
WBL	weight-bearing line

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Niigata University (approval number: 2020-0448). Written informed consent was obtained from all participants.

Consent for publication

Not applicable (the manuscript contains no identifiable individual data or images).

Availability of data and materials

The datasets used in this study are not publicly available to protect patient privacy but are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

T.M. and G.O. conceptualized and integrated the study design.

T.M. and K.S. performed the surgeries, acquired the data and conducted the data analysis.

All authors contributed to drafting the manuscript, and read and approved the final manuscript.

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Figure legends

Fig. 1 Bone cuts in MA, KA/conventional FA and TN-FA

In TN-FA, the tibia is cut perpendicular to its mechanical axis, and only the femur is adjusted within 3° of varus. The inclination of the cut lines is exaggerated for clarity. The dotted line indicates the mechanical axis of the lower limb. M, medial; L, lateral; MA, mechanical alignment; KA, kinematic alignment; FA, functional alignment; TN-FA, tibia-neutral functional alignment.

Fig. 2 Combination of motion capture system and three-dimensional (3D) lower extremity alignment assessment system

Thirty-four skin markers were attached to each participant. Twenty-two of them (12 thigh and 10 shank markers) contained a steel ball so that their two-dimensional (2D) positions could be detected on radiographs. The three-dimensional (3D) positions of the femur, tibia and skin markers were estimated by superimposing 3D bone models created from CT onto the bony outlines of the lower extremity on biplanar radiographs taken under weight-bearing conditions, using 3D-to-2D image registration.

Fig. 3 Gait capture and analysis

A motion capture system (VICON 612, Vicon Motion Systems, Oxford, UK) was set up at the center of the 12 m walking lane, where participants walked at a constant self-selected speed over six force plates. Biplanar radiographs of the lower extremity with the markers in place were obtained immediately after gait capture, and the 3D position of each marker relative to the bones was estimated from its 2D position on the radiographs.

Fig. 4 CPAK classification before and after surgery

The horizontal axis shows aHKA and the vertical axis JLO. Arrows indicate the change in each knee from before to after surgery. After surgery, 11 of 12 knees were within the neutral JLO range (177–183°).

CPAK, coronal plane alignment of the knee; aHKA, arithmetic hip-knee-ankle angle; JLO, joint line obliquity.

Fig. 5 Kinematics of the bony mechanical axes during stance (mean ± SD)

Left column, location (absolute value); right column, translation (change from initial contact). A, B: tibial axis relative to the ground; C, D: femoral axis; E, F: dynamic alignment; G, H: dynamic WBL. Dashed lines, preoperative; solid lines, postoperative. The gray band indicates loading response. p values are for the main effect of condition and the condition × time interaction (Greenhouse–Geisser corrected) in two-way repeated-measures ANOVA. SD, standard deviation; WBL, weight-bearing line; ANOVA, analysis of variance.

Fig. 6 Femoral component position and knee adduction moment

A: Coronal position of the femoral component and postoperative dynamic alignment (mean during stance). B: Coronal position of the femoral component and postoperative peak KAM (stance). The dotted line indicates 3° of varus. C: Individual changes in peak KAM before and after surgery. Squares and error bars indicate mean ± SD. KAM, knee adduction moment.

Tables

Table 1 Comparison of alignment strategies

Strategy	Tibial coronal alignment	Femoral coronal alignment	How balance is achieved
MA	Perpendicular to the mechanical axis	Perpendicular to the mechanical axis	Mainly soft-tissue release
KA	Native joint surface restored (varus accepted)	Native joint surface restored	Bone cuts restore native anatomy
Conventional FA	Adjusted within a set range (varus accepted)	Adjusted within a set range	Bone cuts adjusted on both sides
TN-FA (this strategy)	Perpendicular to the mechanical axis (not adjusted)	Adjusted within 3° of varus	Femoral bone cuts adjusted only

MA, mechanical alignment; KA, kinematic alignment; FA, functional alignment; TN-FA, tibia-neutral functional alignment.

Table 2 Ranges of implant positioning in TN-FA

Component	Direction	Range
Femur	Varus–valgus	Within 3° of varus
Femur	Flexion	0–5°
Femur	Rotation	0–3° external rotation relative to the SEA
Tibia	Varus–valgus	0° (not adjusted)
Tibia	Posterior slope	3°
Tibia	Rotation	Akagi line or ROM method

SEA, surgical epicondylar axis (the line connecting the lateral epicondyle and the sulcus of the medial epicondyle); ROM method, range of motion method (after trial reduction, the knee is flexed and extended and tibial rotation is set where the tibial trial settles).

Table 3 Demographics, clinical outcomes and gait conditions

Item	Preoperative	Postoperative	p value
Age (years)	72.1 ± 6.3	73.0 ± 6.2	< 0.001*[a]

Height (cm)	151.2 ± 4.0	151.4 ± 4.2	0.180[a]
Body weight (kg)	59.2 ± 9.9	59.7 ± 10.5	0.303
BMI (kg/m²)	25.8 ± 3.6	25.9 ± 3.9	0.596
JKOM (points)	56.6 ± 15.8	20.2 ± 14.3	< 0.001*
VAS (0–10)	6.7 ± 1.9	1.0 ± 0.9	< 0.001*
Walking speed (m/s)	0.84 ± 0.18	1.05 ± 0.19	0.008*
Stride length (m)	0.96 ± 0.15	1.09 ± 0.19	0.008*
Stride length / height (%)	63.7 ± 10.2	71.7 ± 12.2	0.010*
Stride time (s)	1.16 ± 0.14	1.04 ± 0.07	0.010*

Mean ± SD. * $p < 0.05$. According to the normality of the differences (Shapiro–Wilk test), the paired t-test or the [a]Wilcoxon signed-rank test was used. BMI, body mass index; JKOM, Japanese Knee Osteoarthritis Measure; VAS, visual analogue scale (within JKOM). Stride length and stride time are values for one gait cycle.

Table 4 Component positions (3D-3D matching on postoperative CT)

Item	Mean ± SD (°)	95% CI (°)	Range (°)
Femur, varus–valgus (valgus +)	-1.8 ± 1.3	-2.6 to -1.0	-3.1 to 0.9
Femur, flexion–extension (extension +)	-2.3 ± 1.7	-3.4 to -1.3	-5.9 to 0.2
Femur, rotation (external +, SEA)	0.1 ± 2.4	-1.4 to 1.6	-3.3 to 4.0
Tibia, varus–valgus (valgus +)	0.0 ± 0.9	-0.5 to 0.6	-1.8 to 1.4
Tibia, flexion–extension (extension +)	-2.1 ± 1.4	-3.0 to -1.2	-4.5 to 0.0
Tibia, rotation (external +)	-5.3 ± 7.9	-10.4 to -0.3	-19.0 to 5.5

Angles relative to the bone coordinate system of each bone. CI, confidence interval; SEA, surgical epicondylar axis.

Table 5 Static alignment

Item	Preoperative	Postoperative	p value
FTA (°)	188.1 ± 4.3	178.3 ± 1.8	< 0.001*
HKA (°, varus +)	10.8 ± 3.7	2.7 ± 1.2	< 0.001*[a]
Static standing WBL (%, medial +)	112.8 ± 27.4	20.7 ± 11.7	< 0.001*
FMA (°)	90.0 ± 2.8	88.3 ± 1.7	0.122
TMA (°)	82.5 ± 3.3	90.0 ± 1.0	< 0.001*
JLO (°)	172.5 ± 4.5	181.8 ± 1.6	< 0.001*
aHKA (°, varus −)	-7.5 ± 4.1	-1.7 ± 2.2	0.002*
JLCA (°, valgus −)	5.3 ± 5.0	-4.8 ± 4.7	< 0.001*

Mean ± SD. * $p < 0.05$. According to the normality of the differences (Shapiro–Wilk test), the paired t-test or the [a]Wilcoxon signed-rank test was used. FTA, femorotibial angle; HKA, hip-knee-ankle angle; WBL, weight-bearing line (center of the proximal tibial articular surface 0%, medial and lateral edges 100%); FMA, femoral mechanical angle; TMA, tibial mechanical angle; JLO, joint line obliquity (= TMA + 180° − FMA); aHKA, arithmetic HKA (= TMA − (180° − FMA)); JLCA, joint line convergence angle.

Table 6 Kinematics of the bony mechanical axes and knee adduction moment during gait

Item	Preoperative	Postoperative	p value
Tibial axis inclination (°, lateral +)			
Initial position	5.2 ± 3.7	0.8 ± 2.2	< 0.001*
Stance, mean	8.7 ± 3.5	3.5 ± 1.9	< 0.001*
Stance, maximum	10.2 ± 3.5	5.3 ± 2.3	< 0.001*
Stance, minimum	4.9 ± 3.8	0.6 ± 2.1	< 0.001*
Loading response, mean	7.7 ± 3.8	2.5 ± 2.2	< 0.001*
Translation, stance mean	3.5 ± 1.1	2.7 ± 1.1	0.053

Translation, loading response mean	1.8 ± 0.6	1.1 ± 0.5	0.001*
Femoral axis inclination (°, lateral +)			
Initial position	-5.9 ± 2.4	0.1 ± 3.0	< 0.001*
Stance, mean	-5.1 ± 2.8	0.9 ± 2.7	< 0.001*
Stance, maximum	-4.1 ± 2.9	2.0 ± 2.9	< 0.001*
Stance, minimum	-7.1 ± 2.3	-1.7 ± 3.3	< 0.001*
Loading response, mean	-5.5 ± 2.7	0.9 ± 2.8	< 0.001*
Translation, stance mean	0.8 ± 1.4	0.8 ± 0.8	0.969
Translation, loading response mean	0.2 ± 0.7	0.6 ± 0.6	0.067
Dynamic alignment (°, varus −)			
Initial position	-11.2 ± 5.1	-0.7 ± 3.7	< 0.001*
Stance, mean	-13.8 ± 5.3	-2.6 ± 3.9	< 0.001*
Stance, maximum	-10.8 ± 4.9	-0.2 ± 3.8	< 0.001*
Stance, minimum	-15.3 ± 5.4	-5.4 ± 5.5	< 0.001*
Loading response, mean	-13.2 ± 5.4	-1.5 ± 4.0	< 0.001*
Translation, stance mean	-2.7 ± 1.2	-1.9 ± 1.1	0.004*
Translation, loading response mean	-1.6 ± 0.8	-0.5 ± 0.7	< 0.001*[a]
Dynamic WBL (%, medial +)			
Initial position	101.9 ± 34.8	6.1 ± 24.2	< 0.001*
Stance, mean	124.3 ± 39.3	20.4 ± 20.2	< 0.001*
Stance, maximum	140.0 ± 39.0	36.0 ± 22.8	< 0.001*
Stance, minimum	95.8 ± 32.0	-12.8 ± 21.4	< 0.001*
Loading response, mean	120.7 ± 39.5	14.2 ± 20.7	< 0.001*
Translation, stance mean	22.3 ± 11.6	14.1 ± 11.1	0.013*

Translation, loading response mean	14.7 ± 8.3	5.3 ± 5.8	0.004*
Knee adduction moment (KAM, %BW·Ht)			
Stance, maximum	4.0 ± 1.1	2.8 ± 0.8	< 0.001*
Loading response, peak	4.0 ± 1.1	2.8 ± 0.8	< 0.001*

549 Mean ± SD. * $p < 0.05$. According to the normality of the differences (Shapiro–Wilk test), the paired t-test or the [a]Wilcoxon signed-rank test was used. Bone axis
550 inclination is the angle relative to the vertical in the coronal plane of the floor coordinate system. Initial position, value at initial contact; translation, change from
551 initial contact; loading response, 0–20% of stance. KAM, knee adduction moment (normalized to body weight and height).

552

553 **Table 7 Comparison of waveforms (two-way repeated-measures ANOVA: condition [preoperative, postoperative] × time)**

Parameter	Phase	Location: main effect of condition	Translation: main effect of condition	Condition × time interaction
Tibial axis inclination (°, lateral +)	Stance	< 0.001*	0.053	0.215
Tibial axis inclination (°, lateral +)	Loading response	< 0.001*	0.001*	< 0.001*
Femoral axis inclination (°, lateral +)	Stance	< 0.001*	0.969	0.011*
Femoral axis inclination (°, lateral +)	Loading response	< 0.001*	0.067	0.030*
Dynamic alignment (°, varus −)	Stance	< 0.001*	0.004*	0.049*
Dynamic alignment (°, varus −)	Loading response	< 0.001*	0.001*	< 0.001*
Dynamic WBL (%, medial +)	Stance	< 0.001*	0.013*	0.165
Dynamic WBL (%, medial +)	Loading response	< 0.001*	0.004*	0.005*

554 * $p < 0.05$. The main effect of condition indicates a difference in the level of the whole waveform (location, position; translation, magnitude of change from initial
555 contact), and the interaction indicates a difference in waveform shape. Interaction p values are Greenhouse–Geisser corrected (identical for location and translation).
556 ANOVA, analysis of variance.

557

558 **Table 8 Correlations of postoperative static parameters and component positions with gait parameters**

Gait parameter	**FTA**	**HKA**	Static standing WBL	**JLCA**	Tibial component (valgus +)	Femoral component (valgus +)
Tibial axis, mean	0.309	0.530	0.327	0.858	-0.215	-0.511
	(0.328)	(0.076)	(0.299)	(< 0.001)*	(0.502)	(0.090)
Femoral axis, mean	-0.257	-0.564	-0.300	-0.543	0.198	0.553
	(0.421)	(0.056)	(0.343)	(0.068)	(0.538)	(0.062)
Dynamic alignment, mean	-0.336	-0.663	-0.376	-0.813	0.247	0.646
	(0.286)	(0.019)*	(0.228)	(0.001)*	(0.438)	(0.023)*
Dynamic WBL, mean	0.206	0.567	0.386	0.626	-0.375	-0.401
	(0.520)	(0.054)	(0.216)	(0.029)*	(0.229)	(0.196)
Tibial axis, translation	-0.075	0.274	0.263	0.094	-0.225	0.077
	(0.817)	(0.389)	(0.409)	(0.771)	(0.483)	(0.812)
Femoral axis, translation	0.378[a]	0.483[a]	0.035[a]	-0.371[a]	0.056[a]	0.567[a]
	(0.226)	(0.111)	(0.914)	(0.236)	(0.863)	(0.054)
Dynamic alignment, translation	0.425	0.172	-0.038	-0.184	0.077	0.253
	(0.168)	(0.592)	(0.906)	(0.567)	(0.812)	(0.428)
Dynamic WBL, translation	-0.308[a]	-0.494[a]	-0.091[a]	-0.364[a]	-0.147[a]	0.144[a]
	(0.331)	(0.103)	(0.779)	(0.245)	(0.649)	(0.656)
KAM, peak in stance	0.129	0.233	0.194	0.639	-0.067	-0.772
	(0.689)	(0.466)	(0.546)	(0.025)*	(0.835)	(0.003)*
KAM, peak in loading response	0.126	0.229	0.193	0.605	-0.066	-0.750

	(0.696)	(0.473)	(0.549)	(0.037)*	(0.838)	(0.005)*

Upper row, correlation coefficient; lower row (in parentheses), p value. * $p < 0.05$. Pearson's correlation coefficient was used when both variables were normally distributed (Shapiro–Wilk test $p \geq 0.05$); otherwise [a]Spearman's rank correlation coefficient was used. Gait parameters are mean values during stance (translation, mean change from initial contact). Sign conventions: bone axes, lateral inclination +; dynamic alignment, varus −; WBL, medial +; JLCA, valgus −; HKA, varus +.

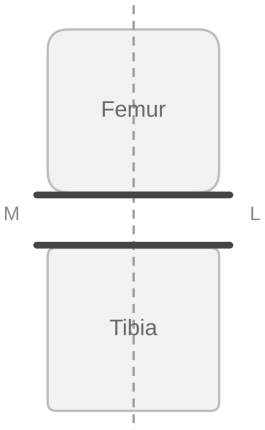
Table 9 Correlations of preoperative static parameters with gait parameters

Gait parameter	**FTA**	**HKA**	Static standing WBL	**TMA**	**FMA**	**JLCA**	MCT coronal inclination
Tibial axis, mean	0.557	0.445	0.394	-0.172	0.070	0.735	-0.310
	(0.060)	(0.147)	(0.205)	(0.592)	(0.828)	(0.007)*	(0.327)
Femoral axis, mean	-0.754	-0.545	-0.820	0.161	0.185	-0.418	-0.052
	(0.005)*	(0.067)	(0.001)*	(0.617)	(0.566)	(0.176)	(0.873)
Dynamic alignment, mean	-0.768	-0.583	-0.694	0.199	0.050	-0.709	0.179
	(0.004)*	(0.047)*	(0.012)*	(0.534)	(0.876)	(0.010)*	(0.578)
Dynamic WBL, mean	0.790	0.662	0.913	-0.258	-0.485	0.275	0.088
	(0.002)*	(0.019)*	(< 0.001)*	(0.418)	(0.110)	(0.387)	(0.786)
Tibial axis, translation	-0.389	-0.115	-0.212	-0.096	0.168	-0.264	0.261
	(0.211)	(0.722)	(0.509)	(0.767)	(0.602)	(0.407)	(0.413)
Femoral axis, translation	-0.157	0.049	-0.131	-0.347	-0.023	-0.489	0.691
	(0.625)	(0.879)	(0.686)	(0.269)	(0.943)	(0.107)	(0.013)*
Dynamic alignment, translation	0.167	0.158	0.040	-0.309	-0.175	-0.321	0.553
	(0.604)	(0.624)	(0.903)	(0.328)	(0.586)	(0.310)	(0.062)
Dynamic WBL, translation	0.242	-0.062	0.438	-0.050	-0.058	0.049	0.012

	(0.449)	(0.848)	(0.155)	(0.878)	(0.858)	(0.881)	(0.972)
KAM, peak in stance	0.571	0.334	0.351	-0.311	0.437	0.859	-0.085
	(0.053)	(0.288)	(0.263)	(0.325)	(0.155)	(< 0.001)*	(0.793)
KAM, peak in loading	0.533	0.319	0.308	-0.299	0.467	0.860	-0.096
response	(0.075)	(0.313)	(0.330)	(0.344)	(0.126)	(< 0.001)*	(0.766)

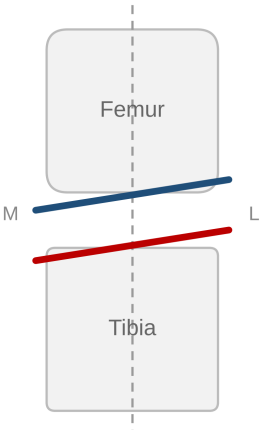
Upper row, correlation coefficient; lower row (in parentheses), p value. * $p < 0.05$. Pearson's correlation coefficient was used when both variables were normally distributed (Shapiro–Wilk test $p \geq 0.05$); otherwise [a]Spearman's rank correlation coefficient was used. Gait parameters are mean values during stance (translation, mean change from initial contact). Sign conventions: bone axes, lateral inclination +; dynamic alignment, varus −; WBL, medial +; JLCA, valgus −; HKA, varus +. MCT, plane fitted to the medial tibial articular surface.

Mechanical alignment (MA)



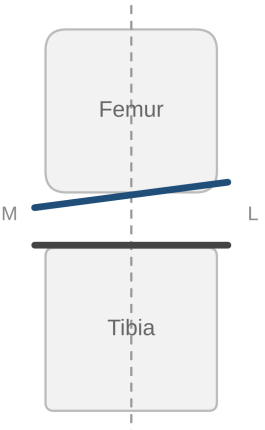
Tibia 90°
Femur 90°

KA / conventional FA



Tibia: varus accepted
Femur: native joint surface

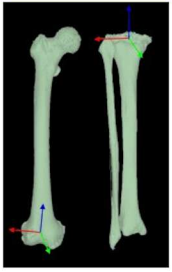
This strategy (TN-FA)



Tibia 90° (fixed)
Femur: varus ≤ 3°



CT

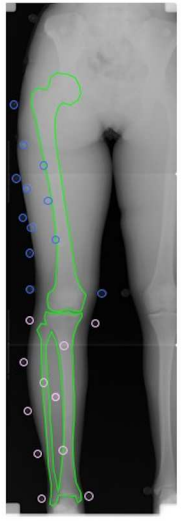


Coordinate system

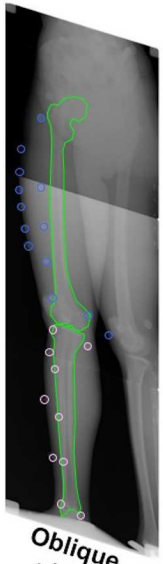




Biplanar X ray and marker position

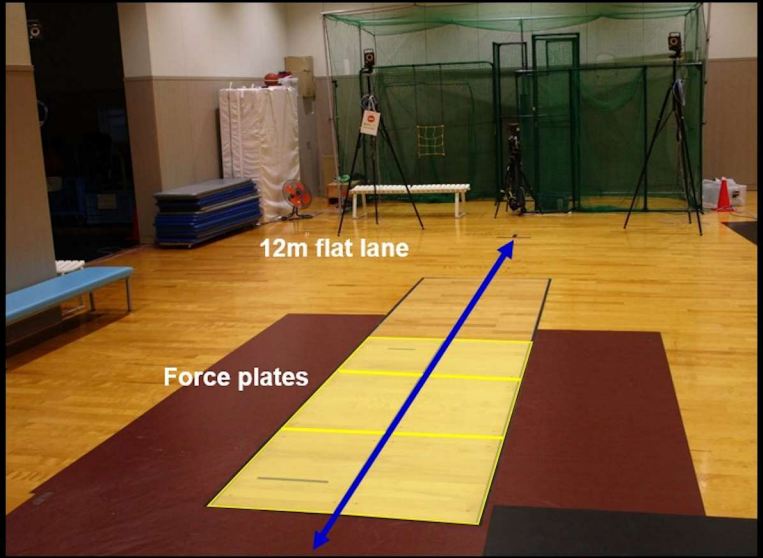


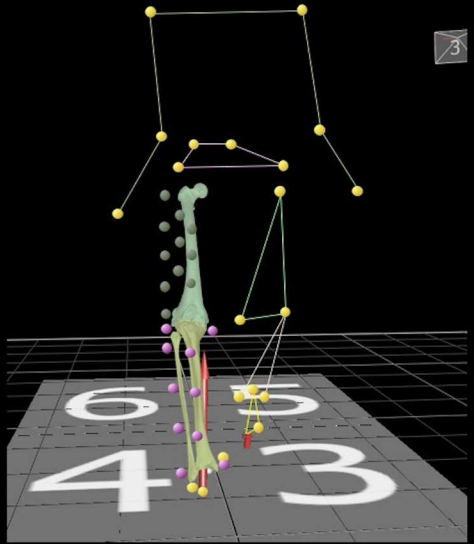
AP plane

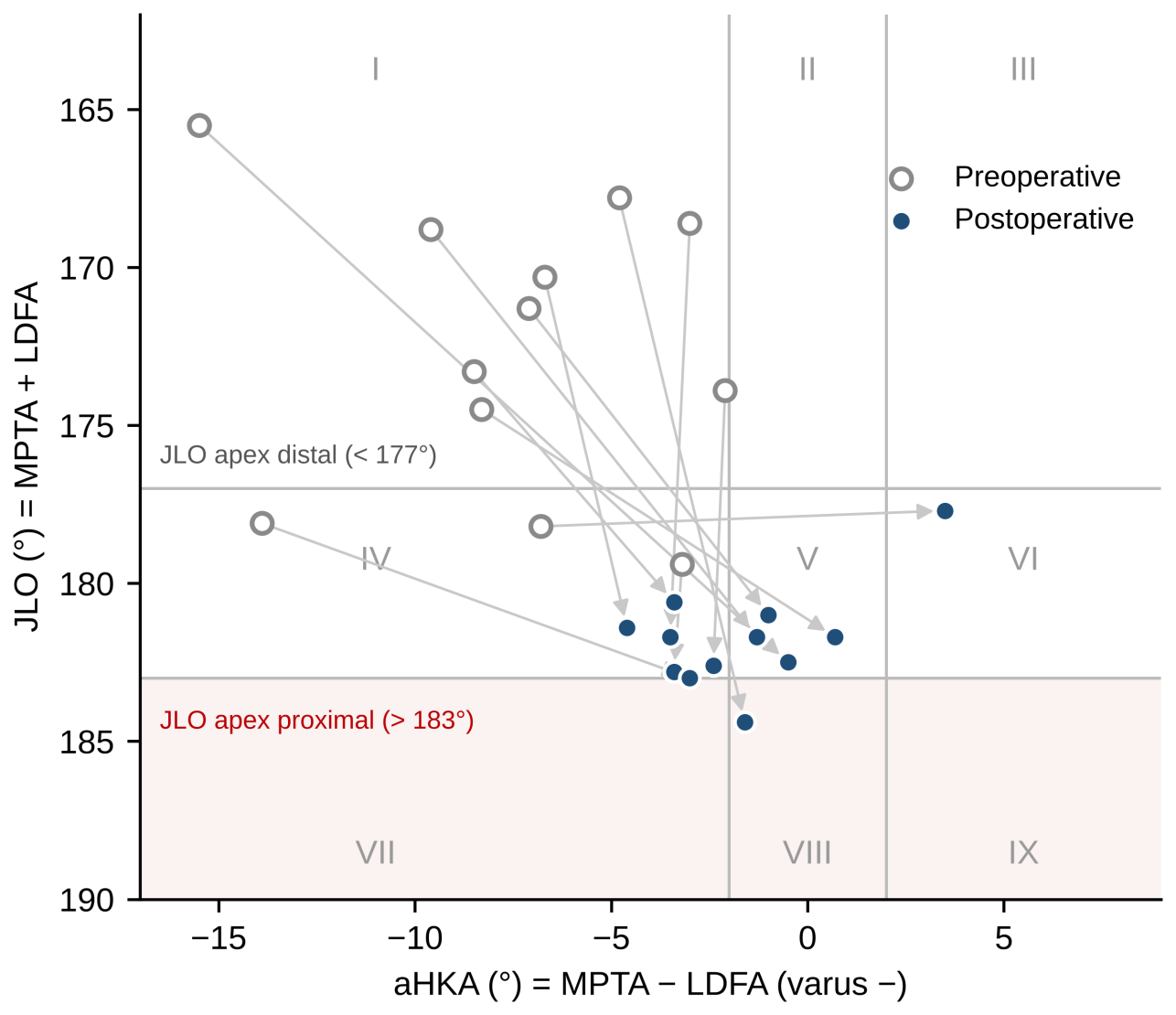


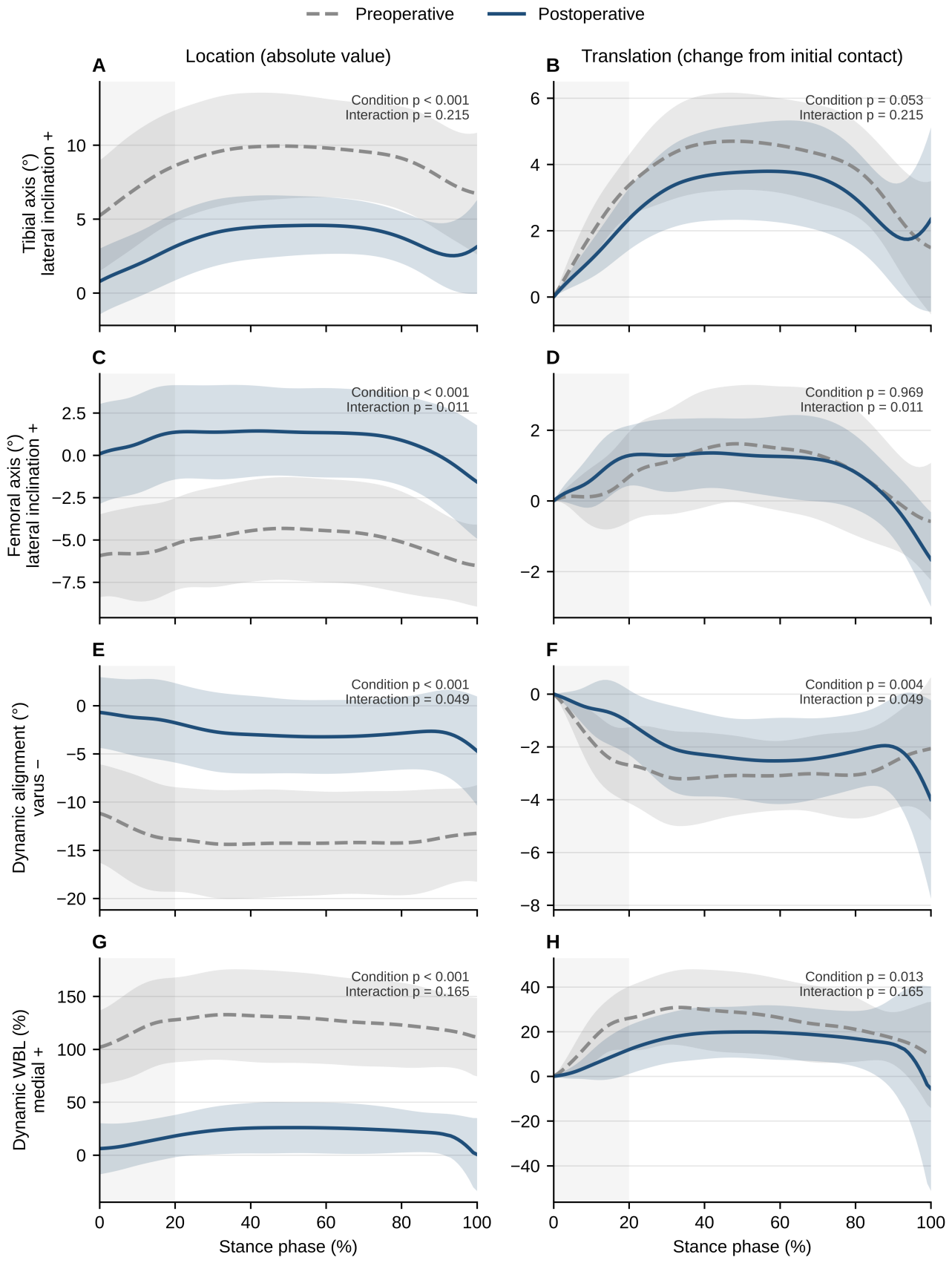
Oblique plane

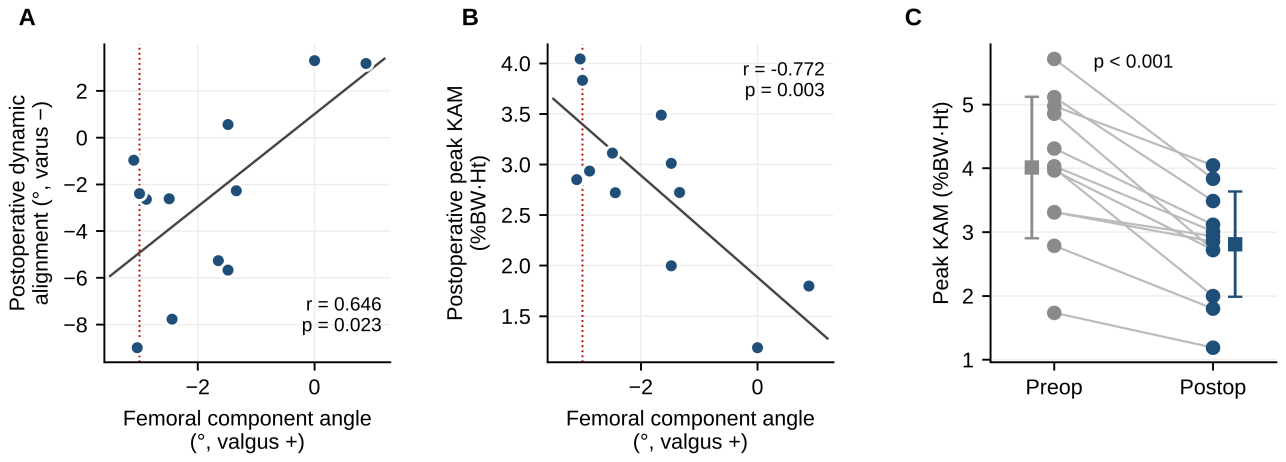
3D to 2D image registration


12m flat lane
Force plates


6
5
4
3


I
II
III
IV
V
VI
VII
VIII
IX
Preoperative
Postoperative
JLO apex distal (< 177°)
JLO apex proximal (> 183°)
165
170
175
180
185
190
−15
−10
−5
0
5
JLO (°) = MPTA + LDFA
aHKA (°) = MPTA − LDFA (varus −)


Preoperative
Postoperative
Location (absolute value)
Translation (change from initial contact)
A
B
C
D
E
F
G
H
Condition p < 0.001
Interaction p = 0.215
Condition p = 0.053
Interaction p = 0.215
Condition p < 0.001
Interaction p = 0.011
Condition p = 0.969
Interaction p = 0.011
Condition p < 0.001
Interaction p = 0.049
Condition p = 0.004
Interaction p = 0.049
Condition p < 0.001
Interaction p = 0.165
Condition p = 0.013
Interaction p = 0.165
Tibial axis (°)
lateral inclination +
Femoral axis (°)
lateral inclination +
Dynamic alignment (°)
varus −
Dynamic WBL (%)
medial +
Stance phase (%)
Stance phase (%)


A
Postoperative dynamic alignment (°, varus −)
2
0
−2
−4
−6
−8
r = 0.646
p = 0.023
−2
0
Femoral component angle (°, valgus +)
B
Postoperative peak KAM (%BW·Ht)
4.0
3.5
3.0
2.5
2.0
1.5
r = -0.772
p = 0.003
−2
0
Femoral component angle (°, valgus +)
C
Peak KAM (%BW·Ht)
5
4
3
2
1
p < 0.001
Preop
Postop