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Kinematic alignment in robotic total knee arthroplasty

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Abstract

Introduction There are two main concepts of total knee arthroplasty: mechanical and anatomical alignment of the lower limb axis. Howell et al. (2013) proposed the concept of kinematic alignment, the main idea of which is to preserve the level of the joint line and the axis of the lower limb that patients had before the onset of osteoarthritis. Initially, kinematic alignment was proposed to be performed with individual guides based on the results of CT/MRI scans but they took a long time to manufacture, were difficult to install, broke down, and were quite expensive. Introduction of robotic orthopaedic systems into clinical practice enabled to plan and perform bone resection with high accuracy, to install the components of the implant system according to the necessary concept thus providing new opportunities for the application of kinematic alignment, which was the purpose of our study.

Objective To study the possibilities of a robotic surgical system in performing restricted kinematic alignment in total knee arthroplasty (TKA).

Materials and methods A prospective single-center study was conducted in 47 patients (12 men and 35 women) with knee osteoarthritis in Kellgren – Lawrence grades 3–4, an average age of 65.87 ± 7.4 years, an average BMI of 31.3 ± 4.7, median HKA angle of 175°, median LDFA of 87°, median MPTA of 87°. The patients underwent robotic total knee arthroplasty (RoTKA) with the method of restricted kinematic alignment.

Results On the control whole-leg radiographs, the average HKA angle after surgery was 176° ± 1.5°. In 42.6 % of cases, the deviation from the plan was within ± 1°, the deviation ± 2° in 44.7 % of cases, and in the remaining 12.7 % of cases the deviation was negative.

Discussion In the literature, we did not find the results of radiographic evaluation of the HKA angle in the coronal view before and after robotic total knee arthroplasty and their comparison with the results of preoperative planning using the kinematic alignment method of the limb axis. The results we obtained show high accuracy of the implementation of the preoperative plan.

Conclusion A personalized approach to TKA with application of an autonomous robotic system effectively provides kinematic alignment of the axis of the lower limb with an accuracy of up to 2° in 87.3 % of patients.

Keywords: knee joint, robot, restricted kinematic alignment, robotic total knee arthroplasty

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INTRODUCTION

The anatomy and biomechanics of a healthy knee joint are constantly being studied and are individually variable. Pathological changes increase the difficulty of orientation in the surgical wound and have an impact on the results of knee arthroplasty [1–6].

At the beginning of total knee arthroplasty (TKR) introduction in the 1970s, the accuracy of the instruments was low and errors during implantation were frequent, so the main efforts were directed at improving the accuracy of implant placement, while reproduction of normal knee biomechanics was the second task [7].

Historically, two main concepts of total knee arthroplasty have been practiced for a long time: mechanical and anatomical techniques of lower limb axis alignment. The basis for the concept of mechanical alignment of the lower limb axis was laid by Inshall et al. and implied restoration o the neutral frontal mechanical axis of the limb and position of the knee joint line parallel to the horizon that improved load distribution on the tibial component and reduced its wear. Based on this concept, instruments were designed and an operating technique was developed [8–10]. The competing technique of Hungerford et al. was based on the concept of anatomical alignment of the limb axis, while the mechanical axis of the limb was also restored to neutral, but the joint line was located within 3° of varus deviation to the mechanical axis of the limb, thus improving knee biomechanics [9, 11, 12].

The philosophy of mechanical alignment is based on the precision of bone resection and the elimination of ligament imbalance by releasing the ligamentous apparatus, which allowed for an increase in the service life of the implants. In anatomical alignment, the ligament balance does not require an extended release, but the difficulty of performing bone resection with a varus angle of 3° resulted in more pronounced deformations, which affected the wear of the implant components and prevented the widespread use of the anatomical alignment technique [12].

A systematic review of studies on gait analysis of patients after TKA undertaken McClelland et al, demonstrated significant kinematic differences compared to normal gait [13]. A study by Bellemans et al. showed that 32 % of men and 17 % of women have constitutional varus of the knee joint of 3° [14]. According to Almaawi et al., the anatomical parameters in 4,884 patients with osteoarthritis during TKR planning varied and that the HKA (Hip-Knee-Ankle) was > 3° in 40 %, > 5° in 19 %, and > 10° in 3 % of patients. Therefore, reconstruction of the neutral mechanical axis in these patients required significant bone resection, caused soft tissue imbalance and problems with joint line orientation, which led to significant changes in knee joint kinematics [3].

Based on these studies, Howell et al. proposed the concept of kinematic alignment, the main idea of which is to maintain the level of the joint line and the axis of the lower limb that patients had before the onset of osteoarthritis [9, 10, 15].

Initially, it was proposed to perform kinematic alignment based on the results of CT/MRI scanning using personalized guides [16, 17]. However, the guides took a long time to manufacture (10–14 days), were difficult to install, broke, and were quite expensive. The use of standard instrumentation does not allow for reliable bone resection for kinematic alignment; the use of computer navigation allows visualization of the limb axis, but does not guarantee the accuracy of the resection, and a special instrumentation or customized implants are very expensive [15].

The introduction of robotic orthopaedic systems into clinical practice allows for planning and performing bone resection with high precision, installing components according to the chosen concept, and provides new opportunities for the use of kinematic alignment [18–23].

The **purpose** of the work was to evaluate the effectiveness of a robotic surgical system in performing restricted kinematic alignment in TKA.

MATERIALS AND METHODS

A prospective single-center study of 47 patients with gonarthrosis was conducted in 2023 at the Clinic of Traumatology, Orthopaedics and Joint Pathology of the University Clinical Hospital No. 1, Department of Traumatology, Orthopaedics and Disaster Surgery of the Sechenov Medical University.

Criteria for inclusion of patients in the study were:

— patients over 18 years old;

— diagnosis of gonarthrosis grade 3–4 according to the Kellgren – Lawrence classification;

— written informed consent for performing TKA according to the proposed technique.

Criteria for noninclusion of patients in the study were:

— risk of anesthesia in physical status greater than ASA 3;

— body mass index (BMI) more than 45 kg/m^2;

— knee joint deformity (varus > 10°);

— valgus deformity of the knee joint;

— extension contracture of the knee joint up to 90°;

— presence of a metal implant on the affected side;

— patients who underwent total arthroplasty of the contralateral knee joint using the mechanical alignment method.

Criteria for exclusion of patients from the study were:

— patient's refusal to continue participating in the study;

— patient's failure to comply with the prescribed regimen.

The study was approved by the institutional ethics committee of Sechenov University (protocol dated 08.12.22 No. 25-22) and registered on ClinicalTrials.gov (ID: NCT05750784). Informed consent from patients to participate in the study was obtained before inclusion in the study.

The study assessed the HKA angle, lateral distal femoral angle (LDFA) and medial proximal tibial angle (MPTA) before and after surgery, which were measured by radiologists together with trauma orthopaedic surgeons in the RadiAnt DICOM Viewer program and were introduced into the database.

Statistical processing of the clinical material was performed using IBM SPSS Statistics 23 (SPSS Inc., Chicago, IL): data grouping, calculation of intensive and extensive indicators, determination of the mean error of relative values, determination of normal distribution using the Shapiro – Wilk criterion. For truly numerical variables (age, BMI, mechanical axis, LDBU, MPTU), frequency histograms and values of statistical parameters were calculated, including the arithmetic mean (M), standard deviation (σ), statistical error of the mean (m), minimum and maximum values, and median (Me). To analyze changes in the parameters over time with a normal distribution before and after surgery, the paired Student's t-test was used, and with an abnormal distribution, the Wilcoxon test. Differences were considered reliable (statistically significant) at $p < 0.05$.

According to the inclusion and exclusion criteria, 47 patients (12 men and 35 women) were enrolled in the clinical study using the continuous sampling method (Fig. 1 a). The affected side was left in 21 and right in 26 patients (Fig. 1 b).

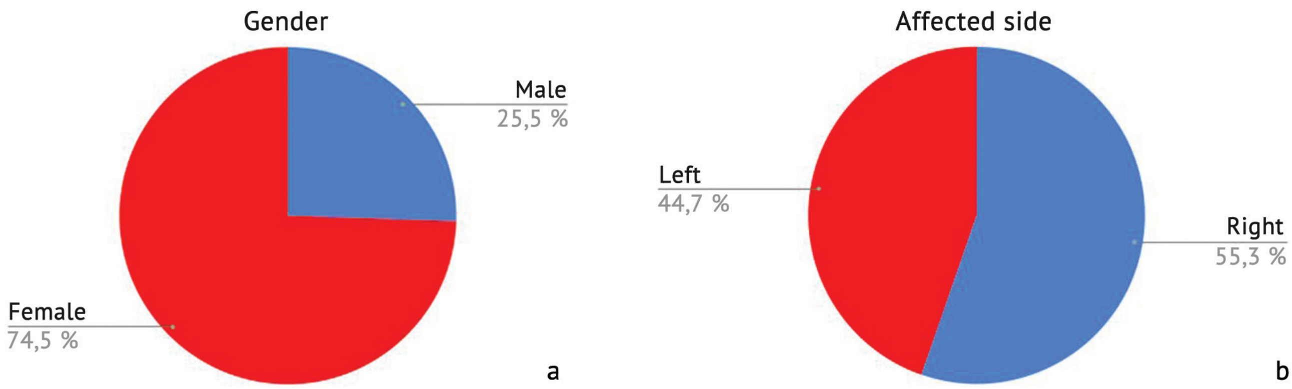

Fig. 1 Distributions of patients according to: *a*) gender; *b*) side affected

The mean age of patients was (65.87 ± 7.4) years (Shapiro – Wilk test, $p = 0.307$), the mean BMI was (31.3 ± 4.7) kg/m² ($p = 0.099$). The median HKA angle before surgery was 175° (min. — 170°; max. — 178°) ($p = 0.093$). The median LDFA before surgery was 87° (min. — 83°; max. — 90°) ($p = 0.002$), the median MPTA before surgery was 87° (min. — 83°; max. — 90°) ($p = 0.006$) (Table 1).

Table 1

Parameters studied

Parameter	Mean value	*p*
Age (years)	65.87 ± 7.4	0.307
BMI (kg/m²)	31.3 ± 4.7	0.099
HKA (°)	175* (min — 170; max — 178)	0.093
LDFA (°)	87* (min — 83; max — 90)	0.002
MPTA (°)	87* (min — 83; max — 90)	0.006

* — median

Analyzing data by age, BMI and mechanical axis, the distribution was normal; the LDFA and MPTA data are assessed as different from the normal distribution (Fig. 2).

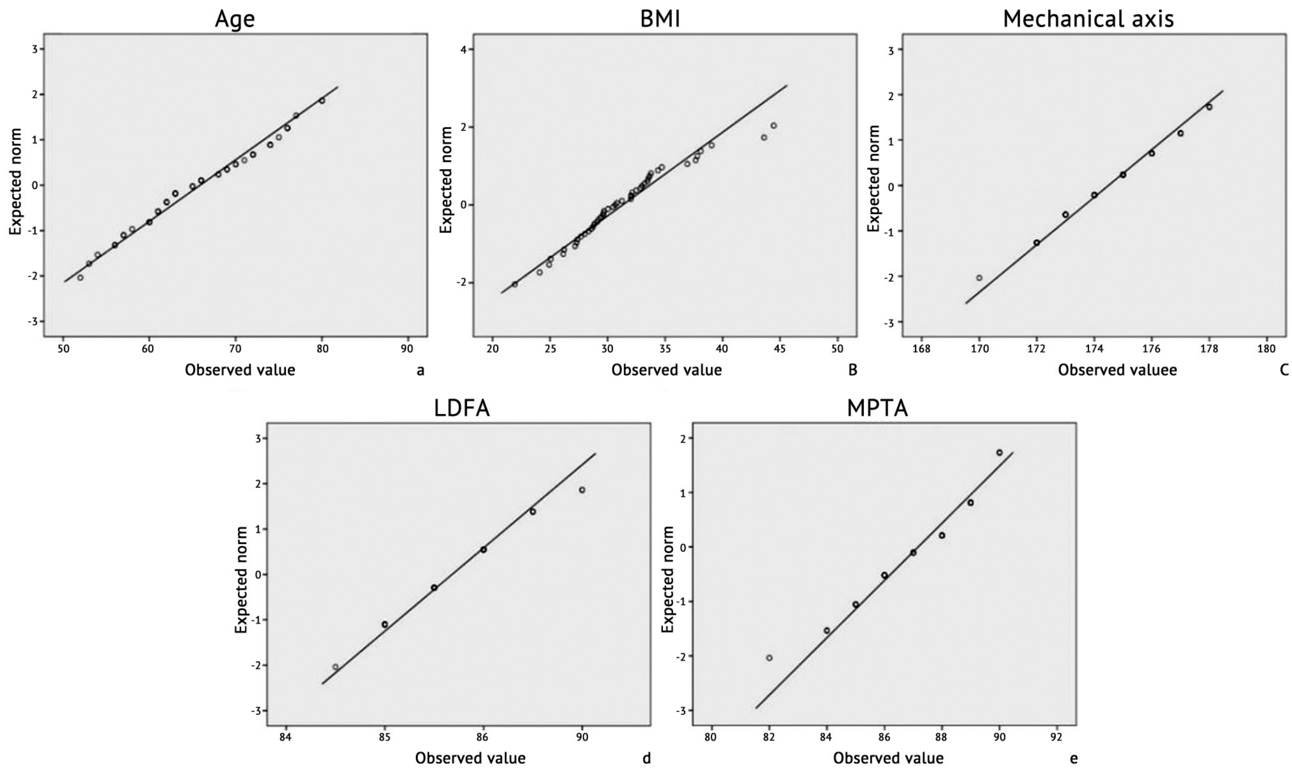

Fig. 2 Data distribution diagrams: *a* age; *b* BMI; *c* mechanical axis; *d* LDFA; *e* MPTA

Technique

To achieve the aim of the study, the autonomous robotic system T-Solution One® (THINK Surgical, Inc., USA) was used. The robotic total knee arthroplasty (RoTKA) technology consisted of three stages: CT examination of the lower extremities, preoperative planning in the TPLAN system, and surgery using the TCAT system.

CT examination was performed with the patient lying on his back with a calibration rod fixed to the affected limb; the results of the study were recorded on a compact disc [21].

The compact disc with the data was loaded into the TPLAN planning system for segmentation of CT slices with subsequent creation of a 3D model of the patient's lower limb. During planning, the TPLAN system allowed choosing a mechanical or a kinematic type of alignment. The unique feature of the TPLAN system is that when choosing the kinematic alignment technique during preoperative planning, it automatically installs the components of the endoprosthetic implant based on the anatomical features of the patient, but allows the surgeon to adjust the position of the implant (Fig. 3).

The planned HKA angle is 177°, as before the state of gonarthrosis developed, the inclination of the knee joint line relative to the horizon is up to 5°. The intact contralateral joint served as a sample. The axis of the lower limb, kinematic axes, such as the supracondylar and longitudinal axis of the tibia, were determined automatically during planning after marking the anatomical structures (head and epicondyles of the femur, centers of the plateau and distal articular surface of the tibia). The patellar axis was not determined, since the patella is not included in the anatomical landmarks in computer planning. The joint line was not measured, but obtained as a result of resection, which leads to an HKA angle of 177°. In mechanical alignment, the planned HKA angle was 180°, the knee joint slope angle was 0°. The plan was approved by the surgeon, and it was recorded on a CD (Fig. 4).

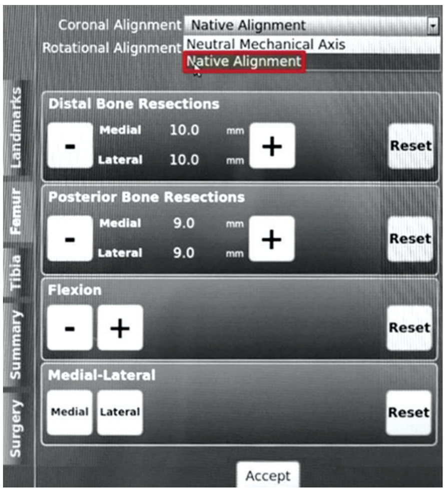

Fig. 3 TPLAN monitor by planning

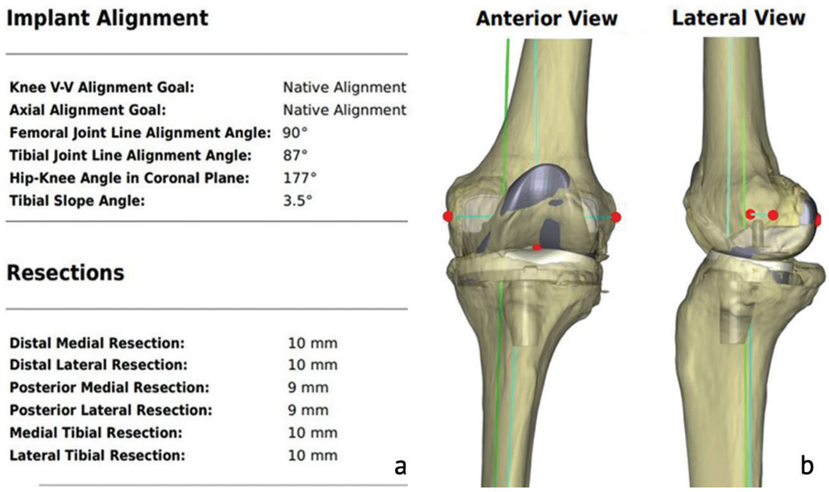

Fig. 4 Preoperative plan: *a* angles of implant placement and bone resection levels; *b* implant placement on the 3D model of the left knee joint

The CD with the approved plan was loaded into the TCAT system. RoTKA was performed using the restricted kinematic alignment technique with the aids of the T-Solution One® autonomous robotic orthopaedic system (THINK Surgical, Inc., USA) under spinal anesthesia without the use of a pneumatic tourniquet, performing a medial parapatellar approach with an outward dislocation of the patella. RoTKA stages: fixation of the lower limb in the leg holder at a flexion angle of 90–100°, surgical approach, fixation of the robot to the patient's limb, digitalization of the knee joint, resection of the articular surfaces of the bones, dismantling of the robot fixators, patellar processing, fitting, assessment of the range of motion, stability of the ligamentous apparatus, implantation of the components and wound suturing (Fig. 5).

Fig. 5 Intraoperative procedures of RoTKA stages: *a* control of the tibial component position; *b* assessment of the mechanical axis; *c* assessment of flexion; *d* assessment of extension; *e* view of the installed implant

All patients underwent TKA with with the Zimmer® Persona implants, which currently have the largest size range, a minimum step of insert thickness of 1 mm, a type of containment with retaining of the posterior cruciate ligament with a fixed insert. Femoral components: standard or narrow, with a cemented fixation of the knee joint implant. Patellar plasty was not performed, only removal of osteophytes and circular denervation.

RESULTS

In the early postoperative period, on the third day, whole lower limb radiography was performed, after which a comparison was made with the preoperative whole-limb radiographs (Fig. 6).

The results of the analysis are presented in Table 2. On the control whole-leg radiographs, the average HKA angle after the operation was (176 ± 1.5)° (paired t-test, $p > 0.01$). In 42.6 % of cases, the deviation from the plan was within ± 1°, in 44.7 % of cases the deviation was ± 2°, in the remaining 12.7 % of cases there was a deviation in the negative direction: from −5° to −3° (Figs. 7, 8). The average value of LDFA and MPTA after the operation was 88° ($p > 0.01$, Wilcoxon test).

Table 2

Analysis of the results before and after the TKA

Value	Before intervention (min/max)	After intervention (min/ max)	*p*
HKA (°)	175 (170/178)	176 (172/179)	< 0.01*
LDFA (°)	87 (83/90)	88 (86/90)	< 0.01**
MPTA (°)	87 (83/90)	88 (84/90)	< 0.01**

Note: * — paired t-test; ** — Wilcoxon test

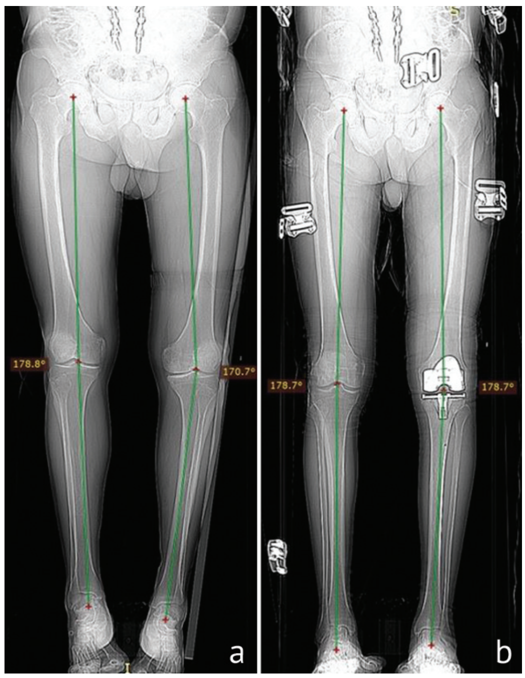

Fig. 6 Whole leg radiographs: *a* before surgery (HKA angle — 170°); *b* after surgery (HKA angle — 178°)

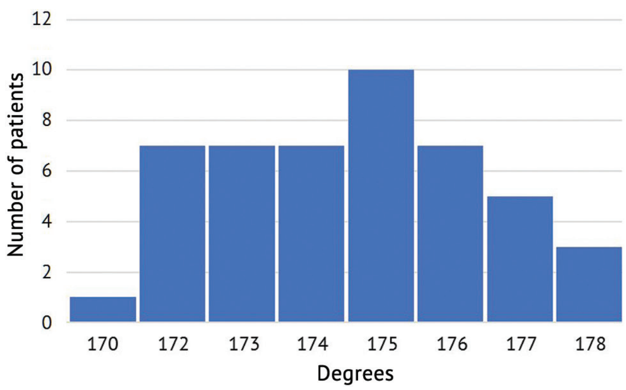

Fig. 7 Histogram of patients' distribution by mean HKA before surgery

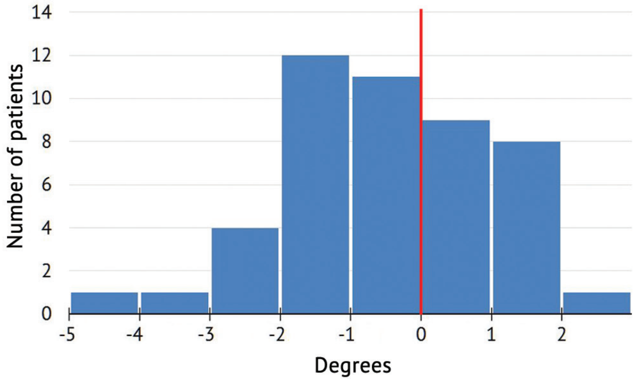

Fig. 8 Histogram of the distribution of the HKA angle deviations from the plan after surgery (red line – planned value 177°)

DISCUSSION

Thus, we obtained the post-surgery HKA angle value of (176.0 ± 1.5)° with statistical insignificance of the paired t-test < 0.01, that is, within ± 2°, deviations from the planned value of 177° were in 87.3 % of patients, and only in 12.7 % of cases the deviation was more than 2°, which is undoubtedly an excellent result.

Massé et al. described a personalized alignment technique, the main goal of which was to reproduce the pre-arthritis tension of the knee ligaments with the aids of a semi-active ROSA Knee system robot and Zimmer Persona implants, using an insert with a Medial Congruent (MC) type of connection, with which the authors implemented a personalized alignment method [24]. However, in their study, the authors do not provide the results of measuring the angles of the limb axis after surgery, limiting themselves to the results of functional scales.

Binfeng et al's meta-analysis conducted a comparison between mechanical (553 cases) and kinematic (559 cases) types of alignment, where functional results were significantly better in terms of WOMAC, KSS scales and range of motion in the kinematic alignment group, but no difference was recorded in terms of radiological indicators (HKA, LDFA and MPTA) [25].

In a study of gait parameters in patients after TKA, Vendittoli et al. showed that patients who underwent surgery using the kinematic alignment technique were closer in their gait patterns to the control group than patients with mechanical alignment of the limb axis [26].

In a retrospective study by Ollivier et al., in which 200 patients were divided into three groups (before surgery with varus, neutral and valgus deformities) and underwent RoTKA using a semi-active robotic MAKO® system (Stryker) according to the kinematic alignment technique. The conclusion was that with kinematic alignment, the femoral component is located in an excessive valgus position and internal rotation in the valgus group and to a lesser extent in the neutral axis group of the knee joint compared to functional alignment [27].

Aflatooni et al. came to the conclusion that functional alignment is a compromise between the mechanical and kinematic alignments that eliminates constitutional varus/valgus deformity, provides flexion up to 90° and avoids ligament damage, but the goal remains the stability and long-term survival of the functioning implant [28].

Morrisey et al. compared RoTKA using the semi-active robotic system VELYS™ (DePuy Synthes, Warsaw, USA) by the kinematic alignment method with the traditional mechanical alignment technique. There were no obvious differences in functional results, including pain, 6 weeks after surgery. After 6 months, patients who underwent RoTKA had a greater range of motion in the knee joint than those in the second group [29].

Kafelov et al. compared two groups of patients (200 cases): patients in one group underwent RoTKA with functional positioning, while in the second group the manual TKA technique with kinematic alignment was used. In the RoTKA group, the scores of the FJS-12 questionnaire were much higher than in the manual technique group [30].

Huber et al. in a retrospective analysis of the use of the semi-active robotic system MAKO® (Stryker) showed that only in 44 % of patients the kinematic alignment technique could be applied and achieve good clinical results [31].

In the available literature, we did not find the results of radiographic study of the hip-knee-ankle angle in the coronal view before and after robotic total knee arthroplasty and their comparison with the results of preoperative planning using the method of kinematic alignment of the limb axis. The results we obtained show high accuracy of the implementation of the preoperative plan.

CONCLUSION

The use of an autonomous robotic system in TKA provides effective kinematic alignment of the lower limb axis with an accuracy of ± 2° in 87.3 % of patients.

Conflict of interests *The authors declare that they do not have conflict of interest.*

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