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ORIGINAL PAPER

Gait analysis and knee joint kinematics before a and 6 month after of corrective valgus osteotomy at patients with medial knee arthritis

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Abstract

Purpose A varus deformity (VD) of the lower limbs results in greater loading of the medial compartment of the knee joint (KJ), leading to its degenerative changes and, eventually, to progressive osteoarthritis (OA) of the joint. The aim of the study was to investigate the mid-term changes in gait biomechanics and clinical symptoms in patients with VD of KJ and OA before and six months after surgical correction.

Methods The study enrolled 25 patients with medial OA of grade 2–3 according to Kellgren-Lawrence and a VD of > 3°, who underwent arthroscopic lavage and debridement of the knee joint followed by corrective osteotomy. The control group included 20 healthy adults. Clinical and biomechanical assessments were done twice: immediately prior to and six months after the surgical treatment. Biomechanical parameters of gait were recorded using an inertial sensor system.

Results According to our findings, there was a statistically significant post-operative increase in the knee extension amplitude by 1.4° in female patients and an insignificant extension increase in male patients.

The mean postoperative KOOS score was 66.7 points (46 to 91) in the patient group, 67.1 points (54 to 91) in males, and 59.5 points (46 to 64) in females. As early as six months after a valgus osteotomy, we already observed improved biomechanics of the KJ motions compared to pre-operative data. By that time, the swing flexion amplitude of the affected KJ had increased and became symmetrical, which had not been the case before surgery. We observed a total of three changes in the KJ kinematics after surgery: increased swing flexion amplitudes in both KJs, a decreased extension amplitude in the affected KJ, and increased first flexion amplitudes in both KJs.

Conclusion According to our study, the midterm outcomes after a valgus osteotomy showed clinical improvements based on the VAS and KOOS scores, which were however less pronounced than in similar studies with a longer assessment term after surgery. We also found a significant increase in the amplitude of joint extension, but only in females. As the function of the operated joint is concerned, valgus osteotomy restored the kinematics of walking movements to a nearly normal gait with increased first and second flexion amplitudes. The function of KJ becomes symmetric though the non-operative side. Thus, the healthy and functionally more capable side is copying the movement pattern of the affected side. Hence, the non-operative leg is functioning less efficiently than it is required by the walking pace.

Keywords Knee joint · Medial knee arthritis · Varus deformity · Valgus osteotomy · Knee joint kinematics

Introduction

A varus deformity (VD) of the lower limbs results in greater loading of the medial compartment of the knee joint (KJ), leading to its degenerative changes and, eventually, to progressive osteoarthritis (OA) of the joint [1, 2]. Corrective osteotomies have been used to treat varus OA since the middle of the twentieth century. Since the 1960s, osteotomies have become a common treatment for this condition. By

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that time, there had already been a certain experience in the surgical technique; indications and contraindications had been stated [3].

Sixty to 80% of the total knee joint load normally passes through the medial compartment, and a VD increases the load [4]. Corrective osteotomies are currently widely used to treat medial OA in patients with VD [5]. Corrective osteotomies are aimed at reducing the load on the affected joint by correcting the limb axis and improving the joint biomechanics [4].

The choice of the valgus correction angle is still a controversial issue, since along with the good outcomes of hypercorrection, there are studies showing no difference between the alignment to the neutral axis and a valgus hypercorrection. For example, a valgus correction of 8–10° is recommended in [6], whereas [7] and [8] recommend respectively 3–5° or 3–6° valgus relative to the mechanical axis. Modern literature most often states the 3–6° valgus hypercorrection range as optimal [1, 9]. In the recent literature, an individualized degree of correction is propagated rather than a uniform correction to the Fujisawa-Region (62–68% of the lateral tibial width) [10]. Recommendations for example ISAKOS exist, but the data differs from one author to another.

The changes in the biomechanical, kinetic, and kinematic parameters of knee motions are likely to depend on the correction angle achieved as a result of the surgery. The pain, maximum knee flexion amplitude, gait velocity, and the knee adduction moment after a VD correction are the key measures of the efficacy of corrective valgus osteotomies in the treatment of medial OA of KJ [11].

The functional and biomechanical outcomes of such osteotomies were evaluated at different time points after surgery. According to a study in patients with bilateral varus, valgus osteotomy improved not only the clinical symptoms but also the biomechanical gait parameters [12]. Among other things, it allows reducing the frontal plane moments at the knee and the joint motions in the same plane.

The study by Bode G et al. [13] assessed the long-term effects of KJ valgus osteotomy for five years. The authors noted stable good functional outcomes throughout a five year follow-up after surgery.

Liu X et. al. in [14] reasonably note that there is currently not enough information on the biomechanical changes associated with KJ OA and the subsequent surgery, including data from patient gait analysis and joint kinematics studies.

KJ OA is associated with the following important changes in the movement biomechanics: KJ hypermobility in the frontal plane, weakness of the quadriceps muscle, and excessive contraction of the knee muscles during movement [15]. It is these phenomena that contribute to further development of the disease. Also, patients with medial OA complain of KJ instability. At the same time, a decrease in the strength of the quadriceps femoris muscle leads to a decrease in the KJ movement amplitude while walking [15]. As observed by Ramsey DK at all in [15], some incompetence of the quadriceps femoris muscle persisted 12 months after a valgus osteotomy and prevented complete extension of the KJ. This is why the authors tend to attach considerable importance to the restoration of the strength of this muscle in the post-operative period.

A later study [16] confirmed that exercising the quadriceps femoris muscle in patients with KJ OA reduced the adverse effects of the disease, such as decreased amplitudes of the KJ motion in the stance phase. Such exercising, among other things, helps increase the amplitudes of the first flexion and the subsequent extension in the single support period. According to our observations, the amplitude limitation is a typical functional manifestation of KJ OA [17].

Thus, mid-term clinical and functional outcomes after valgus osteotomy have not been adequately studied yet.

The study objective

The objective of the study was to evaluate the mid-term clinical and biomechanical outcomes and to analyze the gait biomechanics and KJ kinematics in patients with medial OA of KJ and > 3° VD of the limb, who have had a surgical correction of the limb axis. Changes in the function of the KJ and the biomechanics of walking in general that develop in OA have a long history. For this reason, changes in biomechanics are persistent. However, after surgical treatment for a long time there is an improvement in the condition of patients. What is the physical expression of this improvement? It remains unclear how the kinematics of the KJ changes during walking and whether it changes, taking into account the stability of the motor pattern, in the early stages after valgus osteotomy. Are typical changes in joint function subject to modification after alignment of the anatomical axis of the limb?

We expected that the mid-term outcomes would include a specific improvement in the knee function consistent with clinical improvement.

Materials and methods

The study was performed in accordance with the ethical principles of the Declaration of Helsinki, with obtaining the subject's written informed consent, and was approved by the Independent Interdisciplinary Committee for Ethical Examination of Clinical Trials (No. 6 dated 07.04.2017).

The study enrolled 25 patients with medial OA, who underwent arthroscopic lavage and debridement of the knee joint followed by corrective osteotomy. In our study, the presence of medial gonarthritis and varus deformity more

than 3° was an indication for performing high tibial osteotomy, because there is information about varus deformity up to 2–3° of varus as a norm. We considered that more than 3° of varus is not normal, in the presence of clinical and functional disorders of the knee joint [18].

Inclusion criteria: malalignment < 15°, medial gonarthritis II-III st. according to Kellgren and Lawrence without bone defects; medial compartment chondromalacia according to outerbridge from 2nd–4th; hip-knee-ankle angle more than 3° varus; moderate or high physical activity patient; body mass index (BMI) less than 45 kg/m2; patient age from 30 to 70 years; knee flexion more than 90°; extension deficiency less than 10°; chondromalacia in the lateral compartment and patellofemoral articulation less than 0–1st according to outerbridge; changes in the lateral meniscus no more than 2st. according to Stoller; without ligamentous instability; ineffectiveness of previous conservative treatment methods; pain intensity according to visual analog scale (VAS) ≥ 40 mm.

Our study included patients with variable varus deformity. In patients with varus deformity of 14–16°, in the presence of changes not only MPTA but also LDFA, we performed double-level osteotomy. These patients are referred as another group. We also included these patients in our study because we considered the elimination of varus deformity as the main aspect of treatment and research.

The control group included 20 healthy adults, 14 males, and 6 females; their mean age was 29.7 years. The demographic data of the patient group are presented in Table 1.

Clinical and biomechanical assessments were done twice: immediately prior to and six months after the surgical treatment (Table 2).

Before surgery, the bone deformity and its localization were detected from topograms (teleroentgenograms), by calculating the basic mechanical angles: mLDFA (mechanical lateral distal femoral angle), MPTA (medial proximal tibia angle), and the hip-knee-ankle (HKA) angle [19]. Six months after surgery, the follow-up topograms (teleroentgenograms) were performed to assess the deformity correction rate based on the above mechanical angular measures [19].

The clinical evaluation of the knee function was performed using the KOOS (Knee Injury and Osteoarthritis Outcome Score), and the knee flexion–extension amplitude was measured by method described by Roos EM and Lohmander LS [20]. The pain was assessed using the VAS (Visual Analog Scale) [21], and movement amplitudes were measured with a standard goniometer.

The state of the articular cartilage and menisci was first assessed based on MRI data and then finally during knee arthroscopy. The articular cartilage damage was graded according to the ICRS classification [22]. Assessments of the medial compartment of the joint found ICRS grade 4 chondromalacia of the medial condyle of the femur in 22

Table 1 Demographic data of the patient group

Parameter	Males	Females	Total
Number	12	13	25
Age, yrs	53.25 (39–66)	56 (47–64)	54.7 (39–66)
Height, cm	174 (162–183)	162.5 (153–168)	168 (153–183)
Body weight, kg	84.4 (62–123)	89.2 (68–104)	86.9 (62–123)
BMI, kg/m^2	27.9 (19.8–36.7)	34.5 (27.6–44.4)	31.34 (19.8–44.4)

Table 2 Radiological clinical data of patients, pre-op and 6-month post-op

Parameter	Males		Females		Total	
	Pre-op	Post-op	Pre-op	Post-op	Pre-op	Post-op
Before correction (“+” varus, “-” valgus)	8.1 (4–16) $p = 0.002$	1.17 (1.4–3.5)	7.4 (3–17) $p = 0.002$	1.7 (2–4.6)	7.7 (3–17) $p < 0.001$	1.4 (2–4.6)
MPTA,°	84.3 (82–86.1) $p = 0.002$	90.9 (89.4–94.6)	84.6 (80–87.4) $p = 0.003$	91.2 (87.2–93.2)	84.5 (80–87.4) $p < 0.001$	91 (87.2–94.6)
mLDFA,°	89.2 (85.9–95) $p = 0.29$	87.8 (85.4–91.1)	89 (87–96) $p = 0.374$	88.3 (87.1–90)	89.1 (85.9–96) $p = 0.149$	88 (85.4–91.1)
Flexion amplitude,°	121.3 (100–130) $p = 0.084$	117.9 (113–123)	112.3 (90–130) $p = 0.638$	114.2 (88–123)	116.6 (90–130) $p = 0.475$	116 (88–123)
Extension deficit,°	2.7 (0–10) $p = 0.068$	1.3 (0–5)	2.7 (0–10) $p = 0.028$	1.3 (0–5)	2.7 (0–10) $p = 0.005$	1.32 (0–5)
KOOS score	49.8 (26–81) $p = 0.008$	67.1 (54–91)	33.7 (14–55) $p = 0.0015$	59.5 (46–64)	41.4 (14–81) $p < 0.001$	66.7 (46–91)
VAS, cm	6.4 (5–8) $p = 0.002$	2.6 (1–3)	7.5 (4–9) $p = 0.0015$	3.2 (0–6)	6.9 (5–9) $p < 0.001$	2.7 (0–7)

patients with and ICRS grade 3 in three patients; ICRS grade 4 chondromalacia of the medial condyle of the tibia was detected in 20 patients and ICRS grade 3 in five patients. Assessments of the lateral knee compartment found ICRS grade 2 chondromalacia of the lateral condyle of the tibia in eight patients, ICRS grade 1 in 16 patients, and one patient without chondromalacia. ICRS grade 1 chondromalacia of the lateral condyle of the femur was detected in seven patients; 18 patients had no chondromalacia.

The meniscal damage was assessed according to the Stoller classification [23]. Grade 2 medial meniscus damage was detected in four patients, grade 3A in seven patients, and grade 3B in 14 patients. Grade 1 lateral meniscus damage was detected in 11 patients and grade 2 in four patients, and ten patients had no lateral meniscus damage.

Surgical technique

The surgery was performed under spinal anaesthesia. The first stage included arthroscopic lavage and debridement of the KJ.

High tibial osteotomy was performed as described in [24] from an oblique 5–6-cm incision in projection of tibial medial condyle. The bone was cut till lateral cortical, without cutting the cortex. The osteotomy wedge was opened to a certain size at the pre-operative period corresponding to the size of the tricalcium phosphate block. After that, an electron-optical converter control was performed. Fixation of the osteotomy zone was done by using locking plate (Otis + SBM, France).

If a distal femoral osteotomy had to be performed, it was done as the first stage in order to avoid errors when correcting the limb mechanical axis according to the procedure described in [25] with the use of a locking plate system (DePuy Synthes Tomofix, USA). Four patients in the study had a marked deformity that required a two-level osteotomy.

Pooling somewhat different patient groups in the study, we were driven by the fact that, although being different, the surgical operations were, in the first place, aimed to restore the limb axis and reduce the load on the medial compartment of the joint, and to improve the joint alignment, an important factor influencing the stereotyped gait pattern. A similar approach has been described in the literature [26].

Post-operative management

In the post-operative period, we did not use immobilization of the knee joint for early activation and restoration of knee motions. Loading the operated leg was not allowed (the patients had to walk with crutches) for up to six weeks after high tibial osteotomy and for up to ten weeks after a two-level osteotomy, following which the patients switched to walking with a cane for another six weeks. In the post-operative period — during the transition from crutches to a cane — patients got intensive rehabilitation.

Gait biomechanics analysis

Biomechanical parameters of gait for both sides were recorded using an inertial sensor system ('Trust-M' by Neurocor Ltd., Moscow, Russia). Five sensors were applied at the sacrum, the middle third of the thigh, and the outer ankles of both legs. Gait analysis was performed while walking on a flat surface (floor) at an arbitrary pace. Approximately 20–30 walking cycles were recorded (not including the first and last steps), for which the average parameters were automatically calculated. Defective strides, stops, and turns were excluded from the analysis as described earlier [17, 27]. Temporal, dynamic, and kinematic parameters were recorded. The temporal parameters included GC (gait cycle duration, in seconds) and SDS (period from the start of the GC of one leg until the other leg comes into contact with the support (after swing), % of GC). The dynamic parameter was the amplitude of impact load at the beginning of stance phase (at the contact with the support) and was measured in *g* (acceleration due to gravity). The kinematic parameters were the amplitudes and phases of hip and knee motions (Fig. 1) and were measured in the primary motion direction, i.e., in the sagittal plane (flexion–extension).

For the hip joint, we recorded maximum flexion amplitude at the start of SP (A1, °) and its phase (X1, % of GC), as well as maximum extension amplitude at the end of SP (A2, °) and its phase (X2, % of GC).

For the knee joint, we measured the amplitudes and phases of the first flexion (A1 and X1, respectively), extension (A2 and X2, respectively), and second flexion (in the swing period) (A3 and X3, respectively).

In the abduction, adduction and rotation planes, we recorded the total range of motion.

The obtained data were processed using standard ANOVA methods of the Statistica 12 package. The numerical data are presented as medians and quartiles (25th percentile, 75th percentile). As the sample size was small, no normality tests were performed, and the significance of the differences was assessed using the Wilcoxon-Mann–Whitney test with $p < 0.05$. Changes in parameters were calculated as the difference between pre-operative and post-operative values.

Results

Clinical data

The radiological clinical parameters of the study population before and 6 months after the corrective surgery are presented in Table 2. A residual varus deformity was detected

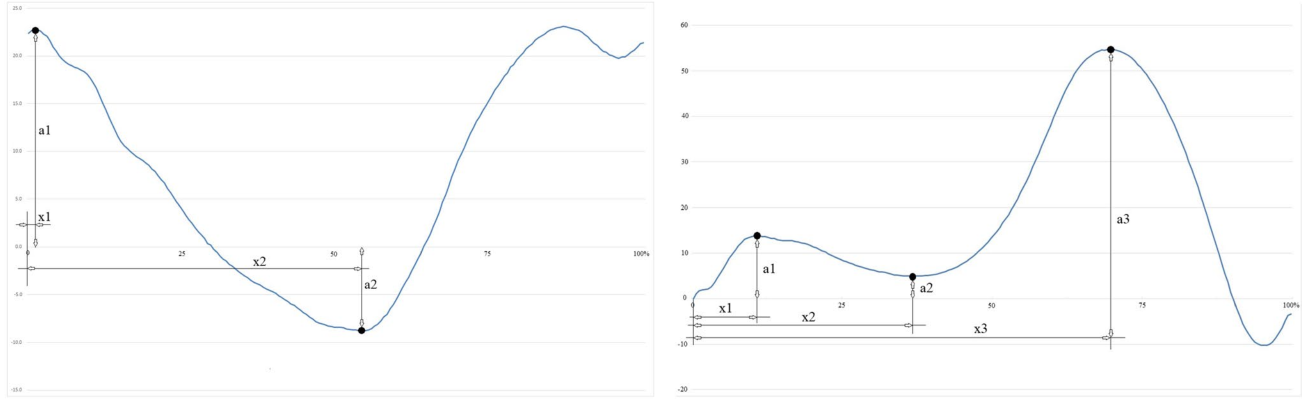

Fig. 1 Measured amplitudes (A) and phases (X) in hip (left graph) and knee (right graph) goniograms are shown in the average graphs

in three patients, its mean angle being 1.3° (ranging 0.5 to 2°). Taking into account the residual varus deformity, the mean angle of valgus correction was 1.4° (from − 2 to 4.6°) in the patient group, 1.17° (− 1.4 to 3.5°) in male patients, and 1.7° (− 2 to 4.6°) in females. Mean MPTA was 91° (87.2 to 94.6°) in the patient group, 90.9° (89.4 to 94.6°) in male patients, and 91.2° (87.2 to 93.2°) in female patients. Mean mLDFA was 88° (85.4 to 91.1°) in the patient group, 87.8° (85.4 to 91.1°) in male patients, and 88.3° (87.1 to 90°) in female patients.

The mean post-operative KOOS score was 66.7 points (46 to 91) in the patient group, 67.1 points (54 to 91) in males, and 59.5 points (46 to 64) in females. The mean flexion amplitude of the joint was 116° (from 88 to 123°) in the patient group, 117.9° (113 to 123°) in males, and 114.2° (88 to 123°) in females. The mean extension deficit was 1.3° (0 to 5°) both in male and female patients. The pain intensity decreased to a mean of 2.7 cm (0 to 7 cm) in the patient population, 2.6 cm (1 to 3 cm) in males, and to 3.2 cm (0 to 6 cm) in females.

The post-operative changes in the radiological clinical data were significant ($p < 0.05$) for all parameters except LDFA and the knee flexion amplitude, which were insignificant both in males and females, and the increase in the extension amplitude, which was statistically significant in females but not in males.

Biomechanical data

The results of biomechanical assessments are shown in Tables 3, 4, and 5.

The temporal parameters of gait cycle and the magnitude of impact load did not change from pre-operative levels and did not differ significantly from the control group.

Changes in hip motion amplitudes and phases are given in Table 4.

Six months after surgery, there was a significant increase in the flexion amplitude of the affected limb at the beginning of the stance phase (Ha1) ($p = 0.034$) by 4.1° compared to that before surgery. Compared to the control group, however,

Table 3 Temporal parameters of gait cycle and impact load amplitude at the beginning of stance phase. Comparison of non-operative versus affected limbs before and after surgery

Parameter	Pre-op		6 months post-op		Control
	Non-operative	Affected	Non-operative	Affected	
GC	1.2[1.1;1.3] $p = 0.617$* $p = 0.157$#	1.2[1.1;1.3] $p = 0.449$* $p = 0.164$#	1.2[1.2;1.3] $p = 0.107$#	1.2[1.2;1.3] $p = 0.167$#	1.2 [1.1;1.2]
SDS	49.8[49.2;50.3] $p = 0.738$* $p = 0.599$#	49.7[49.3;50.2] $p = 0.432$* $p = 0.320$#	49.9[49.5;50] $p = 0.226$#	49.9[49.6;50] $p = 0.349$#	50.1 [49.5;50.3]
Load	− 1.6[− 1.8; − 1.4] $p = 0.069$* $p = 0.293$#	− 1.5[− 1.8; − 1.4] $p = 0.484$* $p = 0.201$#	− 1.7[− 1.8; − 1.6] $p = 0.793$#	− 1.6[− 1.8; − 1.6] $p = 0.299$#	− 1.7 [− 1.8; − 1.6]

*difference from pre-op value; #difference from control

Table 4 Hip motion amplitudes and phases

Parameter	Pre-op		6 months post-op		Control
	Non-operative	Affected	Non-operative	Affected	
Hx1	3.8 [2.3;5.7] $p=0.677$* $p=0.936$#	3.8[2;4.6] $p=0.066$* $p=0.500$#	4.9 [3;5.7] $p=0.226$#	4.3[3.5;5.2] $p=0.793$#	4.3[1.5;5.2]
Ha1	19[16.3;24.1] $p=0.179$* $p=0.001$#	18.3[16.3;20] $p=0.034$* $p=0.001$#	21.6[18.5;27.2] $p=0.018$#	22.4[16.5;24.3] $p=0.001$#	27.4[23.1;29.4]
Hx2	58.3[56.9;60.8] $p=0.747$* $p=0.001$#	59.3[56.9;60.1] $p=0.170$* $p=0.001$#	59[56.8;60.7] $p=0.001$#	59[57.7;61.1] $p=0.001$#	56.0[54.2;57.6]
Ha2	−9.8[−12.5;−8.8] $p=0.706$* $p=0.664$#	−13[−14.9;−10] $p=0.061$* $p=0.123$#	−10.7[−12.9;−7.8] $p=0.900$#	−11.1[−13.2;−8.5] $p=0.837$#	−10.5[−13.4;−7.7]
H_{adduct}	12.2[8.7;16.5] $p=0.904$* $p=0.201$#	11[9.7;14.3] $p=0.689$* $p=0.244$#	13.9[7.9;15.9] $p=0.320$#	13[10;15.9] $p=0.537$#	13.1[10.3;17.6]
H_{rot}	10.1[7.2;13] $p=0.855$* $p=0.044$#	10.7[7.6;13.1] $p=0.346$* $p=0.141$#	10.2[8.3;11.7] $p=0.042$#	9.6[8;12.3] $p=0.066$#	13.0[8.7;15.9]

*difference from pre-op value; #difference from control

Table 5 Amplitudes and phases of KJ motions

Parameter	Pre-op		6 months post-op		Control
	Non-operative	Affected	Non-operative	Affected	
Kx1	16[14.5;18.2] $p=0.101$* $p=0.493$#	16[14.8;18.3] $p=0.189$* $p=0.714$#	16.8[15.1;18.9] $p=0.560$#	16.9[15.5;18] $p=0.936$#	16.9[14.9;18.3]
Ka1	17.4[13.7;21.2] $p=0.046$* $p=0.083$#	14.4[9;19.13] $p=0.128$* $p=0.004$#	18.6[15.1;22.9] $p=0.576$#	17[11.3;20.1] $p=0.013$#	19.1[17.5;23.4]
Kx2	43.9[42.4;45.6] $p=0.853$* $p=0.927$#	41.7[37.3;46.2] $p=0.511$* $p=0.283$#	44.7[39.3;48.5] $p=0.530$#	41[34.7;45.9] $p=0.069$#	44.1[42.3;45.2]
Ka2	9[5.8;11.3] $p=0.067$* $p=0.098$#	8.9[4;12.1] $p=0.009$* $p=0.205$#	9.5[8.5;11.2] $p=0.009$#	10.3[6.7;14.2] $p=0.006$#	5.4[3.7;10.8]
Kx3	75.8[74.9;77.2] $p=0.494$* $p=0.001$#	75.6[74.5;76.3] $p=0.909$* $p=0.001$#	75.6[74.6;77.1] $p=0.001$#	75.3[74.7;76.3] $p=0.001$#	74.2[73.1;75.1]
Ka3	62[57.7;68.1] $p=0.049$* $p=0.005$#	64[55.2;69] $p=0.397$* $p=0.01$#	66.6[59.6;72.1] $p=0.244$#	66.9[63.2;70] $p=0.112$#	68.3[65.7;72.2]
Adduct	10.2[7;14.2] $p=0.368$* $p=0.001$#	10.7[8.7;18.4] $p=0.313$* $p=0.029$#	12[8.4;14.5] $p=0.006$#	11.8[8.5;14.6] $p=0.006$#	15.6[12.0;23.9]
Rot	18[15.7;23.6] $p=0.125$* $p=0.599$#	17.1[13.6; 22] $p=0.757$* $p=0.239$#	17.1[12;20.9] $p=0.077$#	16.4[13.8; 23] $p=0.379$#	19.9[14.9;23.9]

*difference from post-op value; #difference from control

the amplitude was significantly smaller in both non-operative and affected limbs in both male and female patients. According to pre-operative assessments, the amplitude of the non-operative limb was 8.4° smaller than in control ($p=0.001$), and that of the affected limb was 9.1° smaller than in control ($p=0.001$). Post-operative assessments

showed that the amplitudes of the non-operative and affected limbs were smaller than in control by 5.8° ($p=0.018$) and 5° ($p=0.001$), respectively.

The hip extension amplitude (Ha2) showed no significant changes. However, the amplitude phase (Hx2) was significantly increased versus control in both limbs pre- and post-operatively. The pre-operatively measured extension phase in non-operative and affected limbs was 2.3% and 3.3% longer than in control, respectively ($p=0.001$ for both); the post-operative measurements showed a 3% increase of the extension phase versus control in both non-operative and affected limbs ($p=0.001$).

Adduction-abduction ($H_{adduct.}$) did not change significantly. A comparison of pre- and post-operative rotation ($T_{rot.}$) found no significant changes as well. Both pre- and post-operatively, the rotation amplitudes of both lower limbs were smaller than in control, but the difference was significant only for the non-operative limb. The non-operative limb rotation was smaller than in control by 2.9° ($p=0.044$) before, and by 2.8° ($p=0.042$) after surgery.

Knee motions, amplitudes, and phases are presented in Table 5.

Six months after the surgical treatment, the knee first flexion amplitude significantly increased in the non-operative limb ($p=0.046$), but it still remained in both limbs significantly smaller than in control ($p<0.05$). In the operated limb, the amplitude of knee extension in the single support phase decreased significantly compared to that before surgery. Thus, the joint in this phase was flexed more than before surgery. In both knee joints, the post-op amplitude remained significantly smaller than in control. The post-operative swing amplitude increased significantly in both KJs. Moreover, the amplitude values leveled out, which had not been the case before surgery, and they no more differed significantly from the control group ($p>0.05$). Both before and after surgery, the amplitude occurred slightly though significantly later than in the control group.

The adduction-abduction amplitudes of both lower limbs, before and after the surgical treatment, were significantly smaller than in control ($p<0.05$).

Rotation remained without significant changes.

Discussion

The outcomes of valgus corrective osteotomies two years after surgery were evaluated in the studies [28, 29]. That was a considerably longer term than in our study, and not surprisingly their findings, although consistent with ours, surpass them. Another study assessed the outcomes one year after surgery and noted even more significant improvements in the VAS and KOOS scores, which suggest that the clinical outcomes depend on the length of the period after the corrective surgery [30].

According to our findings, there was a statistically significant post-operative increase in the knee extension amplitude by 1.4° in female patients and an insignificant extension increase in male patients. We have not found similar results in the available literature because the authors did not consider this parameter separately but rather assessed the knee range of motion using the KSS score.

Since there are no clear recommendations on maximum and minimum correction of the deformity, the radiological data in the literature vary and largely depend on the preferences and judgment of the operating surgeon, as well as on pre-operative planning and the accuracy of its implementation. Our data on the outcomes of the corrective surgery for VD are comparable with the studies Keyt LK et al. [28].

Thus, the clinical outcomes of our study are consistent with those of other authors. First of all, it concerns a significant 2.5-fold reduction in the pain assessed using the VAS scale, as well as a 1.5-fold knee function improvement based on the KOOS score compared to preoperative data, even as early as six months after surgery. Although our outcomes are not as notable as in the longer post-op studies, they are also statistically significant.

As early as six months after a valgus osteotomy, we already observed improved biomechanics of the joint motions compared to pre-operative data. By that time, the swing flexion amplitude of the affected knee had increased — although not very much (by 3–4°) — and become symmetrical, which had not been the case before surgery. This finding was consistent with the literature data. In the study [31], the post-operative assessments were performed a year after surgery, which is twice as long as in our study. However, the achieved 1–2° increase in the knee range of motion was comparable with our results. We can therefore assume that the range-of-motion restoration occurs within the first six months after the corrective surgery.

We observed a total of three changes in the KJ kinematics after surgery: increased swing flexion amplitudes in both KJs, a decreased extension amplitude in the affected KJ, and increased first flexion amplitudes in both KJs. Increase in the swing flexion amplitude is what is necessary for normal walking. Obviously, the improved conditions of the joint functioning and the decreased OA activity led to an increase in this amplitude. On the contrary, the decrease in the extension amplitude (Ka2) was probably due to yet incomplete postoperative recovery of the KJ. Difficulty with the KJ extension is a frequent symptom in the post-operative period. The fact that a decrease in this amplitude may be an early symptom of knee problems was noted in papers [32, 33]. Possibly, it is not just an early but rather a permanent symptom of developing OA. We also saw it in a study in patients with medial KJ OA

[17], as well as in patients after anterior cruciate ligament (ACL) reconstruction [27]. Similar changes were found in the first flexion amplitude (Ka1), which also decreased both in the acute phase of ACL injury [34] and in the long-term after reconstruction [33]. Thus, the previously described set of symptoms, which includes a decrease in three amplitudes (A1-3) [17] and is typical of medial knee OA, and which we saw before surgery, has significantly improved after it. Six months after surgery, the amplitudes of both flexions increased. So, the typical knee pathomechanics was reversed, which could only be the result of the valgus osteotomy.

The reason of the decreased extension amplitude of the operated KJ in the single support period is still unclear. Our study shows that it could not have been due to a contracture. Therefore, the limitation of extension in this phase is probably of a different nature: a mild pain or the action of the knee flexors. Another possible cause is insufficient recovery of m. quadriceps. Perhaps, envelope EMG of quadriceps and hamstring muscles will help understand it in the future.

There was also an increase in the hip flexion amplitude on the affected side, which, given the unchanged GC, is an indirect indication of increased step length and walking speed. Although the amplitude certainly did not reach normal values, the differences from the control group in the bending amplitude significantly reduced.

We cannot yet explain the increase in the hip extension phase (Hx2). In our further studies, we will try to record the stance phase duration to see whether the increased hip extension phase can be the result of a longer stance phase.

Conclusion

According to our study, the midterm outcomes after a valgus osteotomy showed clinical improvements based on the VAS and KOOS scores, which were however less pronounced than in similar studies with a longer assessment term after surgery. We also found a significant increase in the amplitude of joint extension, but only in females.

As the function of the operated joint is concerned, valgus osteotomy restored the kinematics of walking movements to a nearly normal gait with increased first and second flexion amplitudes. The very important thing is that the function becomes symmetric though the non-operative side, of course, underperforms. But the left–right side symmetry is a more physiological compensatory mechanism. Thus, the healthy and functionally more capable side is copying the movement pattern of the affected side. Hence, the non-operative leg is functioning less efficiently than it is required by the walking pace (GC duration).

Author contribution DS: conceptualization, methodology, writing draft, editing; SK: data curation, investigation, writing draft; AP: data curation, writing draft, editing; AA: data curation, formal analysis, writing draft; EG: writing draft, formal analysis; AN: investigation, formal analysis. All authors have read and agreed to the published version of the manuscript.

Data availability All primary data are with the authors of this study.

Declarations

Ethics approval The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the local ethical committee (Buyanov V.M. Moscow City Clinical Hospital), Minutes No. 06–07.04.17 from 07.04.2017.

Consent to participate All participants have signed the written informed consent form.

Conflict of interest The authors declare no competing interests.

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