



Three dimensional gait analysis in patients with symptomatic component mal-rotation after total knee arthroplasty

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Received: 13 February 2018 / Accepted: 15 August 2018 / Published online: 10 September 2018
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Abstract

Purpose Purpose of the present cohort study was the determination of lower body function and rotation in patients with symptomatic component mal-rotation after total knee arthroplasty using instrumented 3D gait analysis.

Methods A consecutive series of 12 patients (61.3 years ± 11.4 years) were included suffering under remaining pain or limited range of motion at least six months after total knee arthroplasty. A CT-scan according to the protocol of Berger et al. and instrumented 3D gait analysis were carried out including clinical examination, videotaping, and kinematic analysis using a Plug-in Gait model. Outcome variables were temporospatial parameters as well as kinematics in sagittal and transversal plane. Data for reference group were collected retrospectively and matched by age and gender.

Results Temporospatial parameters of the study group showed decreased velocity, cadence, and step length as well as increased step time. Single limb support was reduced for the affected limb. In sagittal plane, maximum knee flexion during swing phase was reduced for the replaced knee joint. In transverse plane, there was hardly any difference between affected and non-affected limb. Compared to the reference group, both limbs show significant increased internal ankle rotation and external hip rotation. There were significant strong linear correlations between ankle rotation and hip rotation as well as ankle rotation and radiological tibial mal-rotation.

Conclusions Patients with symptomatic component mal-rotation after total knee arthroplasty showed typically functional deficits. The affected and non-affected limb showed significant increased internal ankle rotation and external hip rotation, while only the affected, replaced knee showed reduced internal knee rotation. Identification of rotational abnormalities of hip and ankle joints seems to be mandatory in TKA to identify the patient group with external hip rotation, internal ankle rotation, and an elevated risk for symptomatic rotational TKA component mal-alignment.

Keywords Total knee arthroplasty · Component mal-rotation · Unexplained pain · 3D gait analysis

Introduction

Total knee arthroplasty (TKA) is one of the most successful orthopaedic procedures with excellent long-term survivorship [1, 2]. Nonetheless, patients following TKA report unfavourable pain outcome in at least 8.0% and up to 26.5% [3–5]. Compared to unfavourable pain outcomes of total hip arthroplasty, at least 4.8% and up to 20.5%, patients with

TKA show unexplained higher rates [5]. After exclusion of common complications, i.e., instability, infection, component loosening, or material failure [6–8], still 8.2% of patients with TKA remain with unexplained pain [1].

In the past few years, rotational mal-alignment of components has been identified as a factor in pain following TKA [1]. Therefore, in these patients, clinical routine procedure includes computed tomography (CT) scan to evaluate rotational alignment of the replaced joint. Increased internal rotation affecting the femoral, the tibial, or both components occur [1, 9, 10] in 56.4% of mentioned cases. There are several methods to determine rotational alignment using CT scans [11, 12]. Berger et al. established the most common method using bone and implant marks [13]. Although there is awareness of internal rotational errors in patients with TKA, no consensus has been reached on cutoff points

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for the amount of degrees leading to revision [14–16]. This diagnostic procedure in supine position with unloaded legs is limited as a static examination without reflecting the load and dynamic situation during gait.

Instrumented three-dimensional (3D) gait analysis is a reliable diagnostic tool for the detection of gait function [17]. Although mostly used for patients with cerebral palsy, instrumented 3D-gait analysis has already been used for patients following TKA [18, 19]. However, these studies focused on kinematics and kinetics mostly in sagittal and coronal plane, while joint rotation is reflected in transversal plane. Therefore, the purpose of this study was to collect kinematic data, additional in transversal plane, to determine functional knee rotation in patients with component mal-rotation after TKA suffering from unexplained pain and limited range of motion.

Patients and methods

The present cohort study prospectively included 12 patients ($n = 12$; 7 women, 5 men) with a mean age of 61.3 years ($SD \pm 11.4$) at minimum follow-up of six months ($MV = 18.5$ months, $SD \pm 14.6$ months) after osteoarthritis provided with TKA. The patients were recruited from the Out-patient Clinic of our Department for Orthopedics and Trauma Surgery. These patients showed persistent pain or limited range of motion of their artificial knee joint, although there was no clinical, laboratory, or radiological indication for possible instability, infection, component loosening or material failure. Clinical routine procedure demands a CT-scan to determine rotational alignment of the affected limb. In these

cases, supplementary instrumented 3D gait analysis was performed. Exclusion criteria were lack of compliance or inability for gait analysis, preliminary operations of the affected limb, and neurological diseases or such leading to inability. Twelve healthy subjects ($n = 12$) for the reference group were retrospectively collected from the gait data base in the motion analysis laboratory and matched by age ($MV = 58.7$ years, $SD \pm 8.6$ years) and gender (7 women, 5 men). Informed consent was obtained from all patients. The study was approved by the local ethics committee (S-063/2017) and it was conducted in accordance with the Declaration of Helsinki of 1975, as revised in 2008.

Berger-protocol

Rotational alignment was determined with CT-scan by following the protocol of Berger et al. [13]. Femoral rotation was defined as the angle between the posterior condylar line and the surgical epicondylar axis with norm values of 0.3° ($SD \pm 1.2^\circ$) internal rotation for females and 3.5° ($SD \pm 1.2^\circ$) internal rotation for males [13, 20]. Tibial rotation was defined as the angle between the tibial component axis and the tibial tubercle axis with a norm value of 18.0° ($SD \pm 2.6^\circ$) internal rotation for both genders [13]. The patients of this study showed a mean femoral deviation of 1.4° ($SD \pm 2.9^\circ$) external rotation and a mean tibial deviation of 11.8° ($SD \pm 10.9^\circ$) internal rotation (Table 1). Figure 1 shows an example of a well-aligned component and a misplaced femoral component according to the protocol of Berger; Fig. 2 shows an example of a well-aligned and a misplaced tibial component.

Table 1 Clinical and radiological parameters per study group subject

Patient	Clinical parameters			Radiological parameters		
	Range of motion ($^\circ$) of affected knee joint	Femoral antetorsion ($^\circ$)	Tibial torsion ($^\circ$)	Femoral mal-rotation ($^\circ$)	Tibial mal-rotation ($^\circ$)	
1-W	0/0/70	70	0	-14	-0.1	-6.9
2-M	0/5/105	100	10	-23	-5.2	-2.2
3-W	0/2/80	78	5	-8	0.0	0.0
4-W	0/0/55	55	10	-22	0.0	6.2
5-W	0/18/100	82	0	-17	-4.5	11.7
6-M	0/5/110	105	15	-30	-3.8	14.3
7-M	0/5/105	100	15	-10	1.6	15.2
8-W	0/5/95	90	-5	-4	0.6	16.4
9-M	0/15/80	65	10	-20	-3.0	16.7
10-M	0/30/100	70	(-)	-10	-0.4	18.1
11-W	0/0/110	110	10	-28	-5.5	22.8
12-W	0/15/50	35	(-)	-17	3.5	30.8

Mal-rotation difference to norm values of Berger-protocol. Positive component rotation reflects increased internal component rotation; negative component rotation reflects increased external rotation. Norm values: femoral: 0.3° in females, 3.5° in males; tibial 18.0° in both genders

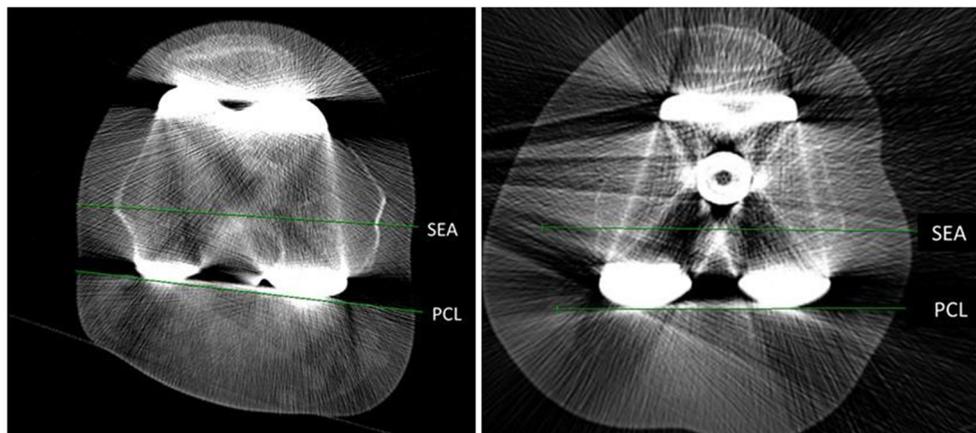


Fig. 1 Comparison of a well-aligned femoral component (left) and a misplaced femoral component (right) according to the protocol of Berger. Left: Femoral rotation of a male right knee defined as the angle between the posterior condylar line (PCL) and the surgical epicondylar

axis (SEA) showing a well-aligned femoral component with an internal rotation of 3° [norm value of 3.5° (SD $\pm 1.2^\circ$) internal rotation for males]. Right: Misplaced femoral component of a male right knee with an internal rotation of 1°

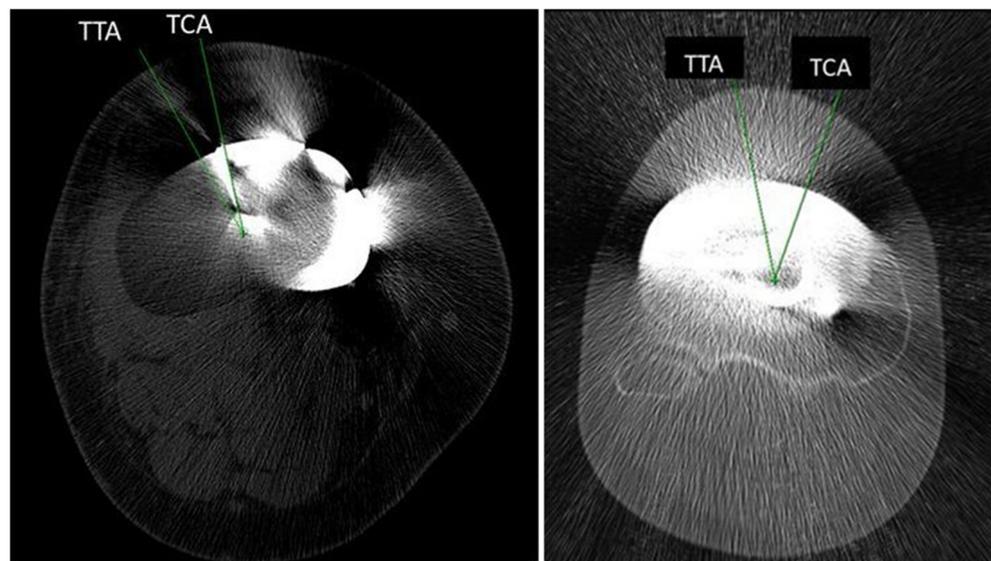
Gait analysis

Instrumented 3D gait analysis was performed by one examiner to a standardized protocol including physical examination, videotaping, and kinematic analysis. Physical examination included clinical parameters as femoral antetorsion and tibial torsion, both measured in prone position with 90° knee flexion. Clinical femoral antetorsion was defined as the hip rotation with best palpation of the femoral trochanter. Clinical tibial torsion was defined as the angle between the axis of the ankle and the direction of the femur. Kinematic analysis was carried out with a 12-camera Vicon system (Oxford Metrics, Oxford, United Kingdom). Patients were equipped with passive markers according to the conventional gait analysis protocol of Kadaba et al. [21]

using the Plug-in Gait (PiG) model. By recording various static trials with additional markers on knee alignment devices, calculation of the rotational alignment of the knee in transversal plane was optimized. Resultant dynamic models were compared with simultaneous videotaping to select the most appropriate static trial with knee alignment device for description of transversal plane. Patients had to absolve barefoot walking on even ground at self-determined walking speed on average during 15 captured dynamic trials. Kinematic data was calculated as the arithmetic mean of recorded walking rounds.

Due to unilateral TKA support in all patients, parameters were separately calculated and analyzed for affected and non-affected limb. Outcome variables of this study were temporospatial parameters and kinematic parameters

Fig. 2 Comparison of a well-aligned tibial component (left) and a misplaced tibial component (right) according to the protocol of Berger. Left: Tibial rotation of a left knee defined as the angle between the tibial component axis (TCA) and the tibial tubercle axis (TTA) showing a well-aligned tibial component with an internal rotation of 18° [norm value of 18.0° (SD $\pm 2.6^\circ$) internal rotation for both genders [13]]. Right: Misplaced tibial component of a left female knee with an internal rotation of 29°



of the sagittal and transversal plane. Maximum and minimum values of knee joint flexion during stance phase and maximum values during swing phase were calculated in the sagittal plane.

To describe joint rotation in transversal plane, mean values during stance phase were calculated for pelvis, hip, knee, ankle, and foot progression. Therefore, angles of pelvis and foot progression were represented by absolute rotations with laboratory axes as fixed elements. Whereas angles of hip, knee, and ankle were represented by relative rotations with proximal segment axes as fixed elements. Pelvic rotation angle was defined between sagittal axis of the pelvis and sagittal axis of the laboratory. Foot progression angle was defined between the long axis of the foot and sagittal axis of the laboratory. Hip rotation angle was defined between sagittal axis of the pelvis and sagittal axis of the thigh. Knee rotation angle was defined between sagittal axis of the thigh and sagittal axis of the shank with untorsioned tibia segments. Ankle rotation angle was defined between sagittal axis of the shank with torsioned tibia segments and the long axis of the foot. Direction of rotation (positive internal vs. negative external rotation) depended on the position of the moving element compared to the fixed element.

Statistical analysis

Statistical analysis was carried out using IBM SPSS Statistics V22.0 (IBM, Armonk, USA). Normal distribution was tested using Shapiro-Wilk test in order to perform two-sampled Student's *t* test for parametric testing or Mann-Whitney *U* test for non-parametric testing. The two independent samples were reflected by the study group and the reference group. Pearson correlation was performed to detect linear correlation between analyzed rotations. Significance level was set at $p = 0.05$.

Results

Clinical and radiological parameters are summarized for each subject of the study group in Table 1.

Temporospatial parameters showed significant differences between study group (SG) and reference group (RG) (Table 2). Representing bipedal parameters velocity (0.89 m/s in SG, 1.30 m/s in RG, $p < 0.001$) and cadence (102.7 steps/min in SG, 113.3 steps/minute in RG, $p = 0.008$) were significantly reduced in study group compared to reference group. Concerning the affected limb as well as the non-affected limb of study group subjects, step length was significantly

Table 2 SG study group, RG reference group

Parameters	Side	SG (MV, SD)	RG (MV, SD)	<i>p</i> value
Temporospatial				
Velocity (m/s)	Both	0.89 (± 0.17)	1.30 (± 0.13)	< 0.001
Cadence (steps/min)	Both	102.67 (± 10.41)	113.34 (± 11.08)	0.008
Step length (m)	Affected	0.52 (± 0.08)	0.69 (± 0.06)	< 0.001
	Non-affected	0.52 (± 0.07)		< 0.001
Step time (s)	Affected	0.59 (± 0.08)	0.53 (± 0.06)	0.004
	Non-affected	0.59 (± 0.07)		0.004
Sagittal				
Max knee flex (stance) (°)	Affected	31.69 (± 9.54)	37.22 (± 6.96)	0.056
Min knee flex (stance) (°)	Affected	5.07 (± 11.71)	0.92 (± 4.70)	0.259
Max knee flex (swing) (°)	Affected	42.54 (± 10.32)	58.23 (± 5.56)	< 0.001
Transversal				
Mean pelvic rot (stance) (°)	Affected	0.44 (± 4.19)	0.42 (± 2.06)	0.986
	Non-affected	0.13 (± 4.04)		0.776
Mean hip rot (stance) (°)	Affected	-11.53 (± 8.11)	-1.45 (± 7.92)	0.001
	Non-affected	-11.08 (± 8.34)		0.002
Mean knee rot (stance) (°)	Affected	2.45 (± 3.21)	5.82 (± 4.80)	0.036
	Non-affected	5.34 (± 4.28)		0.908
Mean ankle rot (stance) (°)	Affected	15.59 (± 9.02)	4.61 (± 7.27)	< 0.001
	Non-affected	15.74 (± 8.72)		< 0.001
Mean foot prog (stance) (°)	Affected	-9.24 (± 4.73)	-9.59 (± 4.03)	0.819
	Non-affected	-8.66 (± 9.39)		0.156

MV mean value, SD standard deviation, Max maximum, Min minimum, Flex flexion, Rot rotation, Prog progression. Rotational analysis: Positive values reflect internal rotation, negative values reflect external rotation

decreased while step time was significantly increased compared to reference group subjects. The affected limb showed a significant decrease in the proportion of single limb support during gait cycle (35.29% in SG, 38.84% in RG, $p < 0.001$) whereas the non-affected limb showed no significant difference (38.02% in SG, 38.84% in RG, $p = 0.307$).

In sagittal plane (Fig. 3), knee joint kinematic values of the affected limb showed no significant differences during stance phase but significant differences during swing phase (Table 2). Maximum knee flexion was significantly reduced during swing phase (42.5° in SG, 58.2° in RG, $p < 0.001$) comparing study group and reference group.

In transversal plane (Fig. 4), absolute rotations of both limbs showed no significant difference between study group and reference group (Table 2). Neither pelvic rotation nor foot progression of the affected as well as the non-affected limb differs significantly.

There were significant differences in all relative rotations of the affected limb (Table 2). Hip rotation was significantly increased towards external rotation compared to reference group (-11.5° in SG, -1.5° in RG, $p = 0.001$). Internal knee rotation is significantly reduced compared to reference group (2.5° in SG, 5.8° in RG, $p = 0.036$). Ankle rotation is significantly increased towards internal rotation compared to reference group (15.6° in SG, 4.6° in RG, $p < 0.001$). Figure 5 shows tibial mal-rotation, ankle rotation, and hip rotation, for the affected limb arranged for each patient of the study group.

The non-affected limb as well showed significant differences in relative rotations (Table 2). Hip rotation is significantly increased towards external rotation compared to reference group (-11.1° in SG, -1.5° in RG, $p = 0.002$). Knee rotation differs not significantly between study group and reference group (5.3° in SG, 5.8° in RG, $p = 0.908$). Ankle rotation is significantly increased towards internal rotation compared to reference group (15.7° in SG, 4.6° in RG, $p < 0.001$).

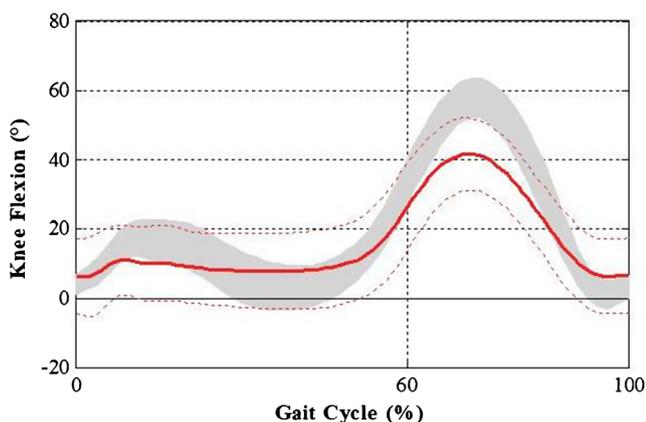


Fig. 3 Knee flexion during gait cycle. Sagittal kinematics for the affected limb. Mean values and standard deviation of the study group (red). Standard deviation of the reference group (gray)

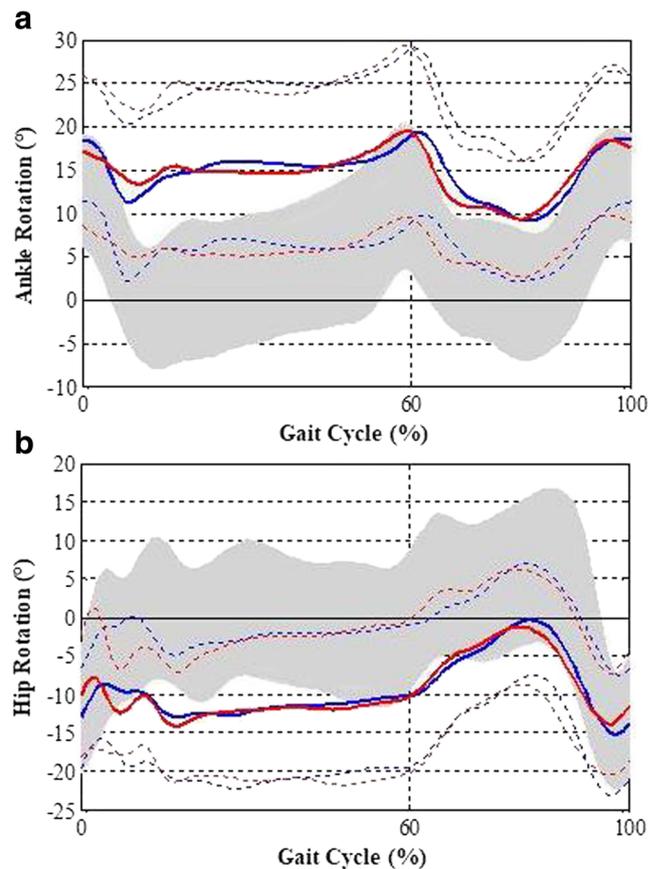


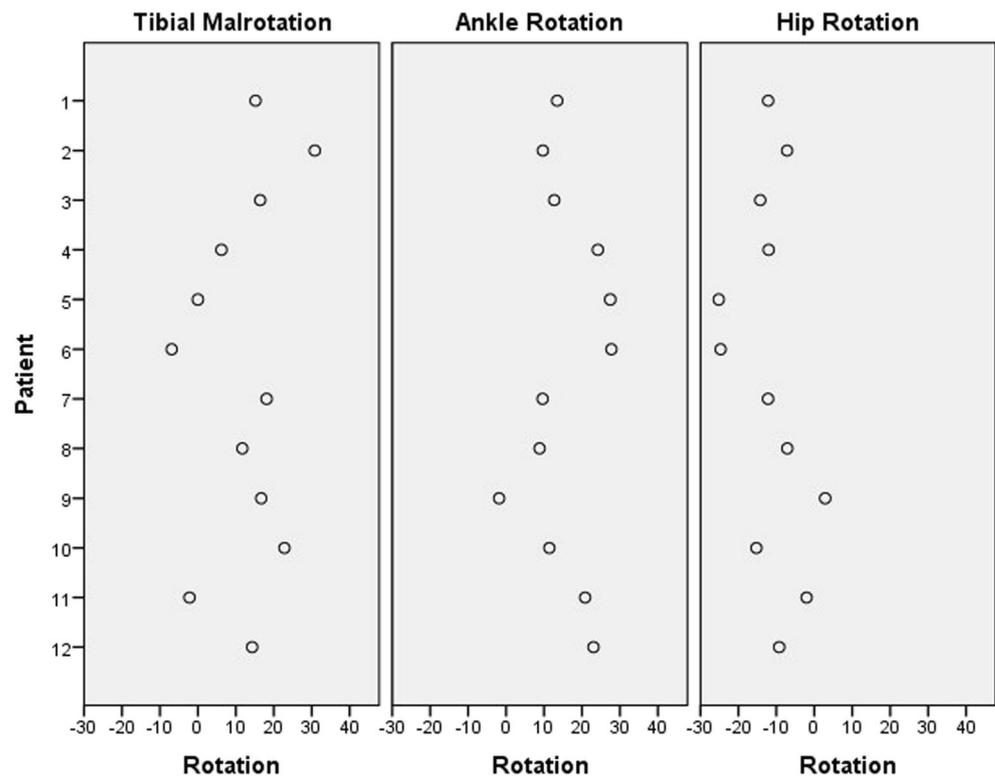
Fig. 4 a Ankle rotation and b hip rotation during gait cycle. Mean values and standard deviations of the affected (red) and non-affected (blue) limb. Standard deviation of the reference group (gray)

For the affected side, Pearson correlation coefficient (PCC) between ankle rotation and hip rotation showed significant strong negative correlation (PCC = -0.667 , $p = 0.018$). Furthermore, significant strong negative correlation appeared between ankle rotation in gait analysis and tibial mal-rotation in CT-scan (PCC = -0.714 , $p = 0.009$).

Discussion

TKA is a successful procedure to relieve pain, correct leg deformity, and help patients resume normal activities with excellent long-term survivorship but there are studies showing high re-admission rates for unexplained knee pain [3–5, 22]. Therefore, the purpose of the present study was a better characterization and comprehension of TKA patients with a history of pain and limited range of motion as well as a radiological component mal-rotation. There are different methods published for measuring component alignment, i.e., using partially loaded plain radiographic measurement as Pedraza et al. [23], two and three dimension radiographic imaging as Sailhan et al. [24] published previously, or using computer tomography what is the

Fig. 5 Tibial mal-rotation ($^{\circ}$), ankle rotation ($^{\circ}$), and hip rotation ($^{\circ}$) for the affected limb arranged for each patient of the study group



actual gold standard to determine component mal-rotation. In the protocol of Berger et al. [13], the patients of this study showed a mean femoral component rotation of 1.4° ($SD \pm 2.9^{\circ}$) to external rotation and a mean tibial mal-rotation of 11.8° ($SD \pm 10.9^{\circ}$) to internal rotation. To best of our knowledge, there have no studies been published providing kinematic data in transversal plane for the lower extremities for TKA patients with symptomatic component mal-rotation. Therefore, advancing questions and hypotheses are a result of the explorative character of the present pilot study.

The results showed significant differences for temporospatial parameters between study group and reference group, i.e., decreased velocity, cadence, and step length but increased step time. This may reflect effects of pain and limited range of motion on gait characteristics. Nonetheless, the pure endoprosthetic replacement of the knee joint as well as increased BMI have to be considered as major confounders [19, 25]. Only the affected limb showed a significant decrease in the proportion of single limb support during gait cycle which reflects reduced support capability.

Maximum and minimum knee flexion during stance phase is not significantly different; however, maximum knee flexion during swing phase is significantly decreased. Despite the abovementioned confounders, patients show not only limited range of motion in clinical examination but also limited functional range of motion. Reflecting the major knee flexion problem during swing phase, our findings may explain the reported problems patients meet in their daily life.

Rotational analysis of the lower body hardly showed any difference between affected and non-affected limb; however, only knee rotation showed a significant difference of the affected limb with reduced internal rotation. This could be explained with the detected internal mal-rotation of the tibial component resulting in a relative external rotation of the tibia and might cause an abnormal Q-angle with altered patella-tracking.

Compared to the reference group, both limbs of the study group showed significant external hip rotation and significant internal ankle rotation of similar extent. Additionally, external hip rotation and internal ankle rotation compensate mutually; therefore, absolute rotations of the pelvis and the foot progression are not significantly different between study group and reference group. These results suggest that a rotational mal-alignment may have already existed preoperatively in the symptomatic knee joints.

Significant strong linear correlation between ankle rotation in gait analysis and tibial mal-rotation in CT-scan was detected. Therefore, pre-operative rotational mal-alignment of the ankle joint may affect the anatomic landmarks used for implantation of the tibial component. The axis of the second metatarsus is used as landmark for the foot axis during surgery as well as during instrumented 3D gait analysis. If the ankle joint was pre-operatively correctly aligned, the ankle joint and the axis of the second metatarsus would indicate tibial mal-rotation by an improbable amount of opposite ankle rotation. If the ankle joint was pre-operatively internally mal-aligned, the anatomic landmarks distant from the knee joint rotate

internal, and a surgeon relying on these landmarks would align the tibial component with too much internal rotation.

Significant differences in knee rotation may reflect the replaced knee joint. But this parameter has to be carefully interpreted because sagittal axis of the shank with untorsioned tibia requires clinically measured tibial torsion for calculation using the PiG model. Pain and limited range of motion made physical examination more difficult and lead to unreliable values of clinical tibial torsion. Further developments in the determination of the knee axis may improve the validity of this parameter.

Between ankle rotation and hip rotation appears significant strong correlation. Therefore, mal-rotation in the ankle joint may be compensated by hip rotation to avoid inwards aligned foot axes.

Study limitations

Several limitations of this study should be mentioned: Firstly, the study group comprises only 12 patients that cannot serve as a random sample representative for the entire population of patients with painful TKA and decreased range of motion. Secondly, palpation of bony landmarks was difficult because all but three patients had an obese body mass index (BMI). Therefore, the projection of bony landmarks on the patients' surface was chosen for marker positioning. Thirdly, determination of knee joint axis using knee alignment devices is inaccurate particularly for the affected limb assuming mal-rotated TKA components. To reduce errors in transversal plane, the best of at least three captured static trials with knee alignment devices was selected to gather sufficient information on rotational alignment. Fourthly, range of motion was additionally limited by patients' pain leading to reduced or evading movements that had an effect on kinematic data. Fifthly, the reference group was only matched by age and gender although there is proof that walking speed and BMI influence temporospatial parameters as well as kinematic parameters. Enduring pain and limited range of motion, patients were not able to regulate their walking speed sufficiently so they were allowed to self-determine their walking speed.

Conclusion

Nevertheless, the present pilot study is the first study analyzing patients with symptomatic component mal-rotation after total knee arthroplasty using 3D gait analysis. In conclusion, these patients show typically functional deficits of the affected limb concerning temporospatial parameters and sagittal knee kinematics. Comparing the instrumented 3D gait analysis data of the affected and the non-affected limb to limbs of a reference group, both limbs show significantly increased internal ankle rotation and external hip rotation, while only the

affected, replaced knee showed reduced internal knee rotation. There are significant strong linear correlations between ankle rotation and hip rotation as well as ankle rotation and radiological tibial mal-rotation.

The surgeon should not rely on knee distant anatomic landmarks for tibia plateau alignment in TKA. A careful clinical examination of the whole lower extremity, looking for rotational abnormalities of hip and ankle joints is mandatory and may help to identify the patient group with external hip rotation, internal ankle rotation, and an elevated risk for symptomatic rotational TKA component mal-alignment.

Further analysis of CT data and correlation with gait data is necessary and may give indications for the association of component mal-rotation with functional rotational mal-alignment of the entire lower body. In addition, different conditions, i.e., stair or ramp ascending and descending, may demand greater rotational ability of the artificial knee joint [26]. Assuming that good outcome is reflected in close-to-normal gait biomechanics, rotational analysis of asymptomatic patients after total knee arthroplasty has to be carried out.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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