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KNEE ARTHROPLASTY

Total knee arthroplasty with unexplained pain: new insights from kinematics

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Abstract

Introduction Up to 20% of total knee arthroplasty patients remain unsatisfied post-surgery, and a large proportion of them report anterior knee pain. This study aims to verify whether patients who experience anterior knee pain after total knee arthroplasty (TKA) will exhibit kinematic characteristics similar to those associated with patellofemoral syndrome, including in the frontal and transverse planes.

Materials and methods Using four different assessment methods [radiological, patient-reported outcome, musculoskeletal assessment with functional performance testing, and a 3D kinematic assessment during gait], the clinical and 3D knee kinematic profiles of three groups were compared: a painful and an asymptomatic TKA group and a healthy control group. All three groups underwent a three-dimensional kinematic knee assessment while walking on a treadmill. Prosthetic component rotation was assessed through a CT scan measurement performed by one experienced radiologist. Flexion/extension, ab/adduction, and tibial internal rotation curves were compared, and significant differences were highlighted through ANCOVA analysis performed on SPSS.

Results A total of 62 knees were evaluated, 24 asymptomatic, 21 painful, and 17 control. A dynamic flexion contracture during gait was observed in the painful group, which was associated with a lack of flexibility of the thigh muscles. Moreover, painful TKA cases exhibited a valgus alignment (− 1.5°) during stance, which increases the *Q* angle and lateralizes the patella. Finally, CT scan evaluation of painful total knee arthroplasty patients revealed that their combined components rotation was in slight internal rotation (− 1.4°, SD 7.0°).

Conclusions Painful TKA patients presented three well-known characteristics that tend to increase patellofemoral forces and that could be the cause of the unexplained pain: a stiff knee gait, a valgus alignment when walking, and combined TKA components slightly internally rotated.

Keywords Total knee arthroplasty · Kinematics · Anterior knee pain · Patellofemoral syndrome · Kinematic knee assessment

Introduction

Total knee arthroplasty (TKA) is recognized as an effective and successful treatment for end-stage knee osteoarthritis [1, 2]. Nevertheless, up to 20% of TKA patients remain unsatisfied post-surgery [3], and a large proportion of them report knee pain [4]. Persistent knee pain can be explained by factors related to prosthesis placement (excessive rotation, aseptic loosening) [5, 6], infections, or surgical procedures (ligament balance, knee instability) [7]. However, in 5–15% of cases where all of these reasons have been ruled out, patients still describe anterior knee pain [8, 9]. Interestingly, the population of patients with patellofemoral (PF) syndrome, who report a similar type of anterior knee pain,

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has shown altered tibiofemoral kinematics, which increase patellofemoral stresses linked to a shift in patellar tracking [10]: dynamic flexion contracture, valgus alignment, valgus collapse, and/or a quick internal tibial rotation movement. However, to our knowledge, no study has yet analyzed the 3D kinematics of painful TKA (including frontal and transverse rotations). Smith et al. [11], in their study of a painful TKA population, only investigated sagittal kinematics, showing that these patients walked with a persistent flexion contracture.

Our hypothesis is that patients who experience anterior knee pain after TKA will exhibit kinematic characteristics similar to those associated with patellofemoral syndrome, including the frontal and transverse planes.

The first aim of this study is to analyze knee 3D kinematics (flexion/extension, valgus/varus, and internal/external tibial rotation) of TKA patients with unexplained anterior knee pain (painful TKA group) and compare them to those of an asymptomatic TKA group, and a healthy control group. The second is to compare clinical assessments (alignment, flexibility) and radiological measures (components' rotation in the axial plane) between the two TKA groups.

Methods

This study was approved by the institutional ethics review boards of the CHUM and the ÉTS and all participants provided informed consent.

Patients

The study population consisted of three groups: 17 healthy subjects (control group), 19 painful TKA patients (21 painful knees), and 20 asymptomatic TKA patients (24 asymptomatic knees).

Control group

The control group included healthy subjects over 38 years of age without any knee pathology, as reported by a trained orthopedic surgeon, and no previous injuries or surgery to the lower limbs. Furthermore, a radiological knee evaluation showed no degenerative changes or pathologies.

TKA groups

TKA patients were divided according to their WOMAC pain score calculated using the Knee injury and Osteoarthritis Outcome Score (KOOS), with a cut-off at 6/20 as the criterion to be included in the painful group [3]. They had to be recruited 12–36 months post-surgery. This time window was selected for various reasons supported by the literature: knee pain stagnates 12 months post-surgery [12]; clinical rehabilitation does not progress after 24 months; and, finally, frontal biomechanics, after strong variations within 6 months post-surgery, remain stable after 12 months [13].

Exclusion criteria included the presence of known TKA knee pain (implant infection/loosening, as assessed by a complete clinical and radiological work-up), presence of another orthopedic pathology in the lower limb, and presence of revision surgery (except for polyethylene revision surgery). No age limit was imposed.

To minimize confounding factors, selected patients had to meet three conditions: their surgery had been performed by one of three experienced orthopedic surgeons (PR, JF and HN) at Jean-Talon Hospital in Montreal (Canada), using the same surgical technique; they had received similar knee implants (a Genesis II or Legion, posterior stabilizing, Smith and Nephew, Auckland, New Zealand); and their patella had been resurfaced.

Fifty-three TKA patients were initially included and underwent assessment. Of these, 14 were excluded for either implant loosening (one patient), or experimental errors during kinematic analysis protocol (calibration errors, KneeKG system falling off during the experiment; 13 patients). Of the 39 remaining patients, 33 had unilateral TKAs and six had bilateral TKAs (for these patients, both knees were included in the study).

Assessments

TKA patients underwent four different evaluations: a radiological assessment, a subjective assessment through patient-reported outcome (PRO), a musculoskeletal assessment by a physiotherapist, including some functional performance testing, and a 3D kinematic assessment during gait. Healthy subjects only underwent subjective, radiological, and kinematic assessments.

Radiological assessment

A single radiologist (DB), blinded to the patients' clinical data, measured component rotation according to Berger's method [14] on CT scans. Normal tibial implant rotation values are known to be −18° (SD 2.6°) for both sexes, whereas normal femoral implant rotation values are different for men (mean −3.5°, SD 1.2°) and women (mean −0.3°, SD 1.2°) [14]. A positive value means an internal rotation and a negative value means an external rotation compared to normative values. We did not find any normative values reported for combined tibial and femoral components. Additionally, a short film X-ray was used to exclude patients who presented loosening. The healthy control group did not undergo the CT scan exam.

Kinematic assessment

All three groups underwent a 3D kinematic knee assessment while walking on a treadmill. A knee harness (KneeKG™, Emovi Inc, Canada) instrumented with reflective optoelectronic markers was installed on the patient's lower limb. This harness significantly reduces soft tissue artifacts, providing a measure of 3D knee kinematics with an accuracy of 0.4° in the frontal plane (varus/valgus) and 2.3° in the transverse plane (tibial rotation). The 3D knee kinematic measures taken with this harness (Fig. 1) have been shown to be repeatable (0.4–0.8° depending on the plane of movement) and reliable (intra class coefficient of 0.88–0.94) [15–17]. The movement of the reflective markers was captured by an infrared camera (Polaris, Spectra, Northen Digital Inc., USA, also widely used for surgical navigation systems) and computed by a software application (Knee3D™, Emovi Inc, Canada). Prior to the gait trial, a calibration procedure using the functional and postural method was performed [16]. Patients were told to walk at a comfortable pace on a treadmill. An in-house MatLab™ (Mathworks, USA) program was used to extract unfiltered kinematics data from the KneeKG™ system. Gait cycles were divided using a method based on minimum flexion. Then, the 15 most repeatable gait cycles were kept for further analysis [18]. Finally, a mean of these repeatable gait cycles was calculated for each patient. The resulting 3D kinematics were flexion/extension rotation, varus/valgus rotation, and internal/external tibial rotation.

Fig. 1 KneeKG™ harness

For each group, mean kinematic curves and standard deviations were calculated for one complete gait cycle (100%). Differences between the groups were analyzed at each percent of gait cycle.

Subjective assessment

Subjective assessment consisted of two patient-reported outcomes, the KOOS and the Lower Extremity Functional Scale (LEFS). The KOOS is composed of five sections including symptoms, pain, quality of life, and knee function during daily activities and sports. Each section of the KOOS is evaluated between 0 (worst situation) and 100 (best situation). The LEFS is more sensitive to post-surgical changes in joint function. It consists of 20 questions rated between 0 and 4. A maximum LEFS score of 80 represents the best functional level [19]. The healthy control group only answered the KOOS questionnaire.

Musculoskeletal assessment

An experienced physiotherapist (ML) performed a clinical musculoskeletal assessment on both TKA groups. Thigh muscle flexibility [quadriceps, hamstring, tensor fascia lata, and iliotibial band (ITB)] was tested using the Thomas, Ober, and SLR tests. Knee stability and range of motion were also evaluated.

For functional performance testing, three tests recognized by the Osteoarthritis Research Society International were assessed (timed up and go, walking 3 m, ascending/descending stairs) [20].

Statistics

Kinematics data analysis was performed using the Matlab™ (Mathworks, USA) statistical toolbox. Subjective, demographic, and all other data were analyzed using Statgraphics Centurion XVI™ (StatPoint Technologies Inc, USA). A power analysis was performed on our primary outcome: a modification of the flexion range during loading. Seventeen patients were needed in each group to measure a 4° reduction in range of flexion/extension during loading ($\alpha < 0.05$ and $\beta < 0.2$) [11].

Assumptions of normality and equality of variances were verified, respectively, with the Shapiro–Wilk and Levene tests. The parameters that were normally distributed underwent a Student's test (*t* test), with a *P* value set at 0.05, or an ANCOVA with two covariates (age and body mass index). The Wilcoxon/Mann–Whitney test was used to verify the null hypothesis for the parameters that did not follow a normal distribution.

Statistical analysis was performed in two stages to capture the impact of the control group. First, both TKA groups (painful and asymptomatic) were compared to each other (Student's *t* test). Second, all three groups (ANCOVA) were compared to account for differences in BMI and age. A Student's *t* test using the Bonferroni correction for independent variables was used for post hoc tests on kinematic data. The level of significance was set at $P < 0.05$.

The statistical significance of categorical variables (clinical assessment) was determined by conducting χ^2 tests on both TKA groups. The level of significance was set at $P < 0.05$.

Results

Demographic results

The control group consisted of 17 healthy subjects, the painful TKA group of 19 patients/21 knees (2 bilateral cases), and the asymptomatic TKA group of 20 patients/24 knees (4 bilateral cases) (Table 1). There were equivalent proportions of females and males in each of the three groups. Mean BMI was higher in the painful TKA group (mean 31.6 kg/m^2, SD 5.3) than in the asymptomatic group (mean 28.3 kg/m^2, SD 3.6 ; $P < 0.05$) and the healthy group (mean 26.0 kg/m^2, SD 3.8 ; $P < 0.01$) (Table 1). Participants in the healthy group were younger (mean 56.8, SD 8.1) than those in both TKA groups (painful: mean 65.0 years, SD 8.3, asymptomatic: mean 69.9 years, SD 7.9, $P < 0.001$). These two factors (age and BMI) were then considered as covariates for further statistical analysis.

Kinematics results

Figure 2 presents the kinematic knee patterns while walking for one complete gait cycle for all three groups: flexion/extension (Fig. 2a), varus/valgus (Fig. 2b), and tibial rotation (Fig. 2c).

Table 1 Clinical and radiological information

Parameters	Asympt Mean (SD)	Painful Mean (SD)	*t* Test *P*	Control Mean (SD)	ANCOVA *P*
n (subjects/knees)	20/24	19/21		17/17	
Sex (%)					
Woman	54.2	57.1	N.S	35.3	N.S
Man	45.8	42.9	N.S	64.7	N.S
Age (year)	69.9 (7.9)	65.0 (8.3)	$P < 0.05$*	56.8 (8.1)	$P < 0.001$*
BMI (kg/m^2)	28.3 (3.6)	31.6 (5.3)	$P < 0.05$*	26.0 (3.8)	$P < 0.01$*
Walking pace (m/s)	0.7 (0.2)	0.8 (0.3)	N.S	0.7 (0.3)	N.S
Time from surgery (year)	2.1 (0.3)	2.0 (0.4)	N.S	N/A	–
Leg with TKA [*n* (%)]					
Unilateral	19 (80%)	17 (89%)	–	N/A	–
Bilateral	4 (20%)	2 (11%)	–	N/A	–
Questionnaires					
LEFS (/80)	66.6 (8.2)	43.6 (13.7)	$P < 0.001$*	N/A	–
KOOS pain	90.0 (11.2)	59.5 (17.7)	$P < 0.001$*	93.1 (15.1)	$P < 0.001$*
KOOS symptom	84.4 (16.0)	62.1 (21.1)	$P < 0.001$*	91.7 (11.6)	$P < 0.001$*
KOOS AVQ	90.0 (10.3)	60.9 (16.3)	$P < 0.001$*	94.0 (14.7)	$P < 0.001$*
KOOS sport	55.0 (23.2)	23.3 (19.1)	$P < 0.001$*	87.2 (22.3)	$P < 0.001$*
KOOS QoL	82.3 (21.1)	43.5 (29.3)	$P < 0.001$*	86.7 (24.4)	$P < 0.001$*
Component rotation					
Tibial rotation (°)	7.8 (5.4)	0.8 (6.8)	$P < 0.001$*	N/A	
Woman	7.4 (6.8)	− 2.6 (4.1)	$P < 0.01$*	N/A	
Man	8.3 (3.6)	2.5 (7.6)	$P < 0.05$*	N/A	
Femoral rotation (°)	− 0.5 (2.3)	− 2.1 (2.6)	N.S	N/A	
Woman	0.7 (1.8)	− 0.5 (2.6)	N.S	N/A	
Man	− 1.8 (2.3)	− 3.0 (2.2)	N.S	N/A	
Combined rotation (°)	7.3 (6.1)	− 1.4 (7.0)	$P < 0.001$*	N/A	
Woman	8.1 (7.6)	− 2.9 (4.1)	$P < 0.01$*	N/A	
Man	6.6 (4.1)	− 0.5 (8.4)	$P < 0.05$*	N/A	

Index: *N/A* non-applicable, *N.S* non-significant ($P > 0.05$)

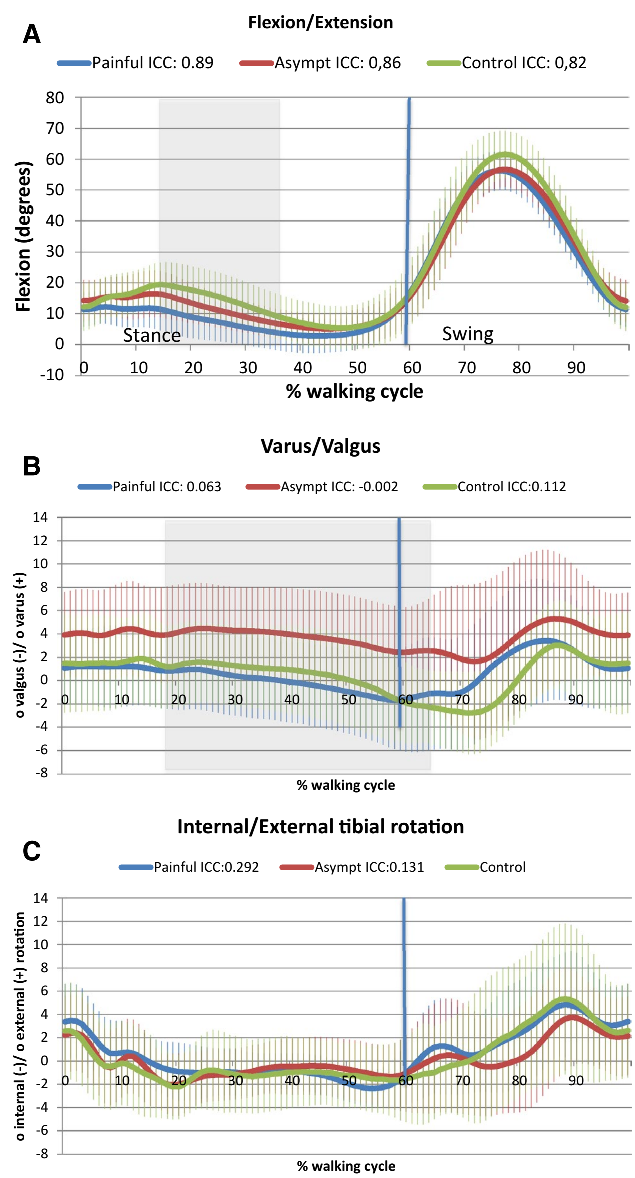


Fig. 2 Kinematics when walking (painful TKA: blue, pain-free TKA: red, healthy subject: green). Gray zones represent sections of the walking cycle where there was a statistical difference between groups ($P<0.05$). Vertical bars represent standard deviation from the mean for each group. **a** In sagittal plane, **b** in frontal plane, **c** in transverse plane

Flexion/extension

A slight dynamic flexion contracture at initial contact, combined with a lower flexion excursion during loading, was observed for both TKA groups, but was more significant in the painful TKA group. Painful TKA group had a mean flexion of 6.5° (SD 9.9°) and asymptomatic group had a mean flexion of 9.9° (SD 5.3°), $P<0.05$ during stance phase (gray zone on Fig. 2a). In other words, both TKA groups presented a flexum compared to the healthy control group, with a more pronounced stiff knee gait in the painful TKA group.

Varus/valgus

Painful TKA patients exhibited a valgus movement during the stance phase starting at 40% of the walking cycle, whereas the asymptomatic group remained in varus (mean adduction of 4° during the first 40% of the walking cycle, $P<0.05$). Yet, both groups presented a similar static alignment on post-operative visual musculoskeletal assessment (no post-surgery long X-rays were available to quantify this value).

During stance phase, the painful TKA group and healthy control groups were similar in varus/valgus angulation (neutral towards slight valgus). For painful TKA patients, a rapid varus movement occurred from the very start of the swing phase, whereas for healthy control and asymptomatic patients, the change to varus occurred later in the swing phase (at about 70% of walking cycle instead of 60%, $P<0.05$).

Internal/external tibial rotation

Internal/external tibial rotation was similar between groups.

Radiological results

The results showed statistically significant differences in tibial and combined tibial and femoral component rotations between the TKA groups. Table 1 presents the values of tibial and femoral component rotation relative to normative values presented by Berger [14] for both TKA groups. Positive values represent an external rotation of the femoral or tibial component, while negative values denote an internal rotation of the component compared to normal.

The mean combined tibial and femoral component rotation showed a slight combined internal rotation (− 1.4°, SD 7.0°) in the painful group, whereas it showed a 7.3° (SD 6.1°) external combined rotation in the asymptomatic group, $P<0.001$.

When analyzing the tibial component alone, values differed between men and women for the painful TKA group. Tibial component in men were − 2.6° (SD 4.1°) internally rotated, whereas women were 2.5° (SD 7.6°) externally rotated compared to normative values. However, mean tibial component of asymptomatic TKA patients showed a significant external rotation of 8.3° (SD 3.6°) compared to normal values and to the painful group ($P<0.001$).

Subjective results

The painful TKA group scored lower in all five KOOS dimensions than did the asymptomatic and control groups (Fig. 3; Table 1, $P < 0.01$). These results are consistent with those of the LEFS questionnaire, which highlighted important limitations for the painful TKA group.

The asymptomatic group showed functional outcomes close to those of the healthy control subjects, except in the capacity to engage in sports and leisure activities.

Clinical results

In both TKA groups, the lower limb had a neutral static alignment in both the sagittal plane (no flexion contracture or hyperextension) and the frontal plane, as visually assessed by the physiotherapist. All patients were able to reach full passive extension, and no difference was observed in total knee range of motion.

Tensor fascia lata muscles appeared retracted for the same proportion of patients in both TKA groups. There were more patients with ITB tension in the painful group (Ober test: ITB tension in 4% of asymptomatic patients versus 38% of painful TKA patients, $\alpha = 0.01$). The Thomas test showed that 58.3% of asymptomatic patients and 71.4% of painful TKA patients presented a retraction of the quadriceps. Finally, painful TKA patients presented a hamstring retraction compared to asymptomatic patients (SLR test: $P < 0.05$). The combination of these elements means that painful TKA patients presented stiffer thigh muscles than asymptomatic TKA patients.

The functional performance testing with the three timed tests showed that they were not more difficult for painful TKA patients than for asymptomatic TKA patients.

Discussion

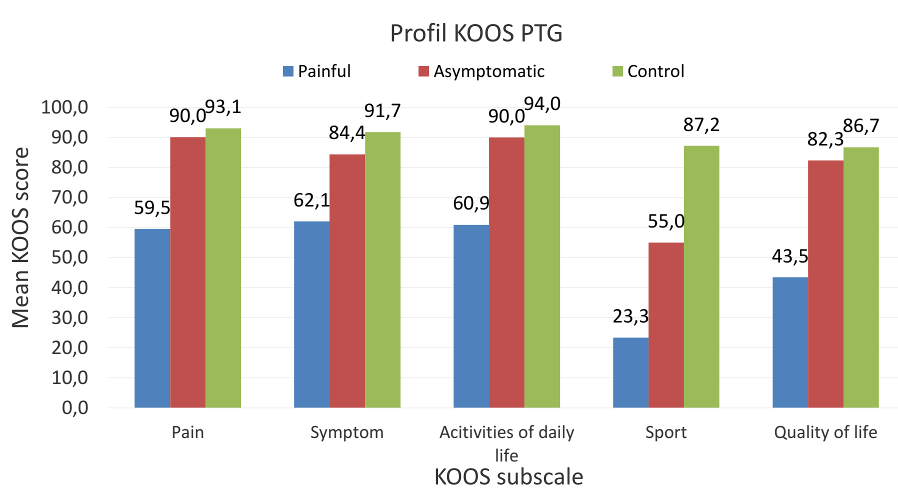
This study aimed at a better understanding of the potential causes of unexplained anterior knee pain in the afflicted TKA population. To this end three groups were compared: a painful TKA group, an asymptomatic TKA group, and a healthy control group. All three groups were similar with respect to demographic characteristics, except for age and BMI. Painful TKA patients were heavier on average than asymptomatic patients and control subjects. However, Mandeville et al. [21] showed that healthy obese persons and normal adults had the same torsors and powers when walking at the same speed. Consequently, BMI values might not influence gait, as confirmed during statistical analysis. Indeed, considering BMI as a cofactor did not affect our findings.

LEFS and KOOS results confirmed that painful TKA patients had lower articular function and presented important limitations in daily life, which supported previous findings [19]. However, functional performance test results were not statistically different between the two TKA groups. These results enhanced our interest in analyzing 3D kinematics of the knee during walking, which is the most common daily activity.

Musculoskeletal assessment results showed lack of flexibility of some muscles (quadriceps, hamstring, and ITB) in both TKA groups, but to a more significant degree in the painful TKA group, suggesting thigh muscles were less flexible in this group.

The painful TKA group presented less ITB flexibility. Previous studies associated ITB lack of flexibility with anterior knee pain. Merican [22] and Sherman et al. [23] highlighted a patella lateralization phenomenon on a bended knee with tight ITB. A tight ITB contributes to unusually high forces between the lateral surface of the patella and the femoral trochlea [23]. These musculoskeletal deficits may explain, at least in part, the pain felt by painful TKA patients, as well as the kinematic differences.

Fig. 3 KOOS results



The CT scan evaluation of component rotational alignment showed that the combined tibial and femoral component rotation for the painful group was slightly internally rotated compared to normative values. Internally rotated TKA components have been recognized as a cause of anterior knee pain [14, 24–27]. An excessive internal rotation of the tibia does in fact involve an altered Q angle followed by abnormal stresses on the patella and surrounding tissue, which could generate pain. A previous study [28] demonstrated that the correction of excessive femoral rotation eliminates anterior knee pain and improves patella tracking. In addition, Thompson et al. [29] showed that the quadriceps strength required to bend the knee was greater in patients with excessive internal femoral component rotation. Thus, lack of flexibility of the quadriceps combined with higher strength demand and excessive internal component rotation could lead to pain and difficulty in performing daily life activities. For this reason, surgeons tend to compensate by placing the components in slight external rotation. This seems to have been the case in the present cohort, where the prostheses components of asymptomatic patients were in external rotation compared to those of painful TKA patients. Present results suggest that slight external rotation of the tibial components is well tolerated by the patients.

The present study revealed that painful TKA patients showed different gait kinematics compared to asymptomatic TKA patients. Indeed, painful TKA patients presented a more pronounced stiff knee gait. This could be explained by a lack of flexibility of their thigh muscle [30]. This stiff and cautious gait during the loading and stance phases was characterized by decreased knee flexion excursion during loading, to stabilize the knee. As this is typical of patients with end-stage osteoarthritis, it might be a compensation that has carried over post-surgery. Some authors have studied pathologies, such as patellofemoral syndrome, which present similar symptoms, and have shown a link between knee pain and flexion contracture during gait [31, 32]. Nadeau et al. [33] reported that patient with PF pain syndrome also reduce their flexion angle during loading phase of the gait cycle to attempt to decrease the PF loads and reduce symptoms.

A kinematic difference in the frontal plane was also observed with an increased valgus at toes off for the painful TKA patients, while asymptomatic TKA patients remained in slight varus. A higher valgus increases the Q angle, which lateralizes the patella and increases patellofemoral stresses [10, 34]. The valgus at toes off could also be related to the ITB lack of flexibility that was observed in the painful TKA group. Nakagawa et al. and Larose [35, 36] showed that a 10° increase in the Q angle led to a 45% increase in maximal pressure under the patella.

During swing phase, the kinematic pattern in the frontal plane changed drastically and evolved very rapidly towards varus for painful TKA patients. To explain this, we hypothesized that painful TKA patients are adopting a gait that avoids causing pain. In other words, the painful knee adopts a varus movement during swing phase to minimize the Q angle and to decrease the pressure under the patella during swing.

This protection mechanism is potentially linked to patients' pre-operative gait, acquired due to knee arthrosis and never corrected [35–37]. During stance phase, kinematics are likely constrained by the prosthesis, thus placing the patella under stress.

There was no contact between bony structures (patella and femoral trochlea) for TKA patients in this study, as is the case in patellofemoral syndrome, since the patella has been resurfaced and the structures in contact with each other are prosthetic structures (polyethylene buttons of the resurfaced patellas against femoral metal implants). Nevertheless, an increase in pressure under the patella due to a valgus alignment of the lower limb, combined with a flexum during stance, could induce pain that is similar to patellofemoral pain. This could be caused by the presence of surrounding tissue, supplied by nerves and blood vessels, or to the synovial plica, infrapatellar fat pad, tendons, retinacula, or capsule, which are very sensitive to pain [9].

Study limitations

This study presents some limitations. Knowledge of patients' pre-surgery clinical states would have provided a more complete painful TKA profile, including establishing whether patients already presented a lack of thigh muscle flexibility and a valgus alignment during walking prior to surgery. Pre-rotation malformities where not assessed either, although it is known that this could impact patients' satisfaction post-TKA [38]. Furthermore, pre-surgical factors such as low back pain [39] have been linked to post-surgical function and pain. These have not been specifically assessed in this study. A long film X-ray of post-surgical knees would have been useful to measure post-operative hip-knee-ankle angles precisely and further explain the impact of lower limb alignment on kinematics and pain. Another limitation is the use of a single instrument to measure pain, the WOMAC pain score. Using a second tool, such as the Pain Catastrophizing Scale, which has been shown to be predictive of pain, could have added to the validity of our results [40–42]. Moreover, even if the prosthetic designs were similar, implant size varied from one patient to another, which could affect the results as well.

The fact that a single radiologist performed the radiological assessment is another limitation. Ideally, at least two radiologists should have performed the measurements, given their known inter-observer variability. However, the radiologist was an experienced practitioner of these assessments, and not associated to the study. Finally, gait analysis is influenced by soft tissue artifacts. The KneeKG system was used to try to limit and reduce those artifacts.

Conclusions

Painful TKA patients presented three well-known characteristics that tend to increase patellofemoral forces and could be the cause of unexplained pain: a stiff knee gait, a valgus alignment when walking, and combined TKA components slightly internally rotated. Kinematic data showed a gait pattern in painful TKA patients that was similar to patients with patellofemoral syndrome. In patellofemoral syndrome, conservative treatments addressing kinematic factors (such as dynamic valgus for example) have been shown to improve symptoms. Therefore, a prospective study would be useful, to assess the impact of personalized conservative management on pain levels and frontal plane kinematics during gait for patients with painful TKA.

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Compliance with ethical standards

Conflict of interest None of the authors have any conflict of interest in this study. It must be mentioned that Alexandre Fuentes is employee at Emovi Inc, the company that commercializes the KneeKG system. Dr Pierre Ranger and Alexandre Fuentes are also shareholders of Emovi inc. In this specific study, the KneeKG system was used as a tool and therefore, we consider that there was no potential conflict of interest for these two co-authors.

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