



## Article

# Femoral Translation in Patients with Unicompartmental Osteoarthritis—A Cohort Study

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**Abstract:** The use of three-dimensional (3D) gait analysis to image femorotibial translation can aid in the diagnosis of pathology and provide additional insight into the severity of KOA (knee osteoarthritis). Femorotibial translation is of particular importance in patients undergoing UKA (unicompartmental knee arthroplasty), as the absence or elongation of ligamentous structures results in changes in the kinematic alignment. The aim of the study was to evaluate the parameters of femorotibial translation in patients with MOA (medial unicompartmental OA). An artificial model was employed to develop a method for calculating femorotibial translation in vitro. In a prospective cohort study, gait data using three-dimensional gait analysis were collected from 11 patients ( $68.73 \pm 9.22$  years) with severe OA scheduled for UKA and 29 unmatched healthy participants ( $22.07 \pm 2.23$  years). The discrete variables characterising femorotibial translation were compared for statistical significance ( $p < 0.05$ ) using the Student's *t*-test and the Mann–Whitney U-test. The results of the study validated an artificial model to mimic femorotibial translation. The comparison of patients scheduled for UKA and a healthy unmatched control group showed no statistically significant differences concerning femorotibial translation in all three planes ( $p > 0.05$ ). However, the PROMs (patient-reported outcome measures), spatiotemporal, and kinematic parameters showed statistically significant differences between the groups ( $p < 0.001$ ). The data presented here demonstrate typical changes in PROMs as well as spatiotemporal and kinematic outcomes for MOA as seen in knee OA. The results of the clinical gait analyses demonstrate individualised femorotibial translation. The extent of individual femorotibial translation may prove to be an important parameter for altered joint kinematics in patients with MOA, especially prior to UKA implantation.

**Keywords:** femorotibial translation; 3D gait analysis; knee osteoarthritis



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## 1. Introduction

Knee osteoarthritis (KOA) is the most prevalent form of osteoarthritis (OA) in the Western world. It is characterised by pain, swelling, stiffness and slow wear. KOA can result in a loss of joint function and a significant reduction in the quality of life of the affected individual [1]. Among the three compartments of the knees, KOA is most commonly observed in the medial compartment [2–5]. The current imaging procedures for the diagnosis of KOA (radiography, computed tomography, magnet resonance imaging) are exclusively static imaging techniques. Functional changes associated with the disease cannot be evaluated [2,3]. The use of dynamic gait analysis has been established as a diagnostic tool for the identification of kinematic changes associated with KOA [3,4,6,7]. Reduced knee flexion at heel strike, reduced knee abduction angle at 50% of stance phase and reduced knee flexion range during gait have been reported in patients with KOA [8]. The femoral condyles' translation relative to the tibia has been the subject of a limited

number of studies, which have yielded heterogeneous results [6,7,9–12]. Consequently, the tibio-femoral movement patterns remain a subject of contention.

Femorotibial translation is of critical importance in patients with medial unicompartmental knee osteoarthritis (MOA), as it is a key parameter reflecting the abnormal loading and wear patterns of the affected compartment of the knee joint [3]. The increased shear forces that act during this phase of the gait cycle result in increased wear and tear, leading to greater cartilage loss. This results in a change in the kinematics of the knee joint and a further increase in femorotibial translation, which represents a sign of early osteoarthritis (OA) [6–8].

In early MOA, mobile-bearing UKA (unicompartmental knee arthroplasty) represents a valid therapeutic option with great advantages for patients. The bearing perfectly conforms with femoral and tibial components and moves completely passively between the femoral and tibial implant [13]. This results in almost physiologic knee kinematics compared with total knee arthroplasty (TKA) [14,15]. UKA involves replacing only the damaged compartment of the knee, thus preserving the healthy bone, cartilage, and ligaments. This leads to a more natural knee function post-surgery. Many patients report high levels of satisfaction with the outcomes of UKA, including improved function and quality of life. The UKA's knee-sparing approach has led to an increase in the number of implanted unicondylar endoprotheses, which, in turn, has necessitated high-quality surgical indications [13,16–19]. The kinematic alignment and, thus, the function of the ligament structures in the knee joint is of particular importance when determining the indication for surgery and implantation of a UKA. A deficiency in the anterior cruciate ligament that becomes apparent during surgery has significant consequences for the patient, as the implant composition must be altered or a total knee arthroplasty (TKA) must be employed [2,7,15].

If the indication is correct, the kinematically aligned UKA represents an alternative knee prosthesis that is more individualised, physiological and anatomical [17]. The ability to adequately visualise femorotibial translation in a preoperative three-dimensional gait analysis would significantly contribute to an even more precise indication for the implantation of a UKA. Consequently, the development of individualised implants in arthroplasty would be further advanced.

Given the growing number of kinematically aligned UKAs, it becomes evident that a functional assessment of the MOA is necessary. The objective of our study was to investigate the differences in femorotibial translation in patients undergoing planned UKA.

## 2. Materials and Methods

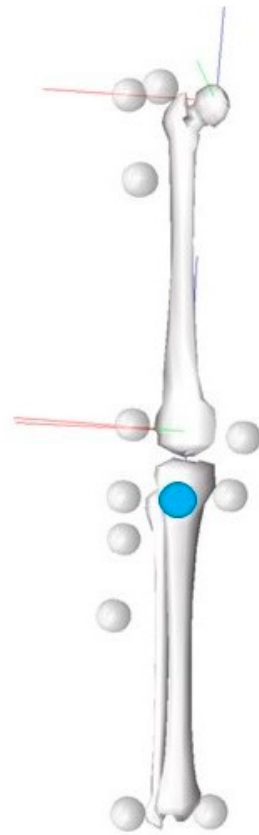
The data used in this study were collected in an in vitro setting and a clinical case-control study. In the first part, an artificial model was used to develop a method for calculating femorotibial translation in vitro using 3D gait analysis. In the second part of the study, the efficacy of a method for visualising femorotibial translation using 3D kinematic motion analysis was evaluated. This was performed through a prospective cohort study that performed an intraindividual comparison of a group with MOA in which UKA is indicated. This was followed by a comparison with a healthy control group.

Emphasis was placed on the loading response in the stance phase of the gait cycle [8]. In our setting, the loading response was defined as the first 12% of the gait cycle. Initial contact was identified using kinematic-based event detection.

### 2.1. Model Analysis

For calculating femorotibial translation in vitro, a virtual marker within the tibial plateau was created by using the analogue marker placements on the medial and lateral edges of the tibia and setting the virtual marker to half the distance between them, where femorotibial translation was expected to be the largest. An anatomical artificial bone model with an implanted medial mobile-bearing UKA with a removable inlay was used. A coordinate system was compiled at the distal end of the femur. The virtual marker is

illustrated in Figure 1. To assess femorotibial translation, the movement of the virtual tibial marker was recorded in the local femoral coordinate system and calculated as ROM in the loading response for the anterior–posterior, medio–lateral, and cranio–caudal axes of the averaged movement.



**Figure 1.** Marker system with the virtual tibial marker (blue).

In the *in vitro* model, the differences between a physiological and a pathological movement with increased femorotibial translation were recorded using an anatomic model of the knee with the implanted mobile-bearing UKA, a removable inlay and springs applied to mimic ligament tension [20].

## 2.2. Clinical Study

From 2021 until 2022, patients with an indication for a medial UKA at a university medical centre were included in the prospective cohort study. Participants completed the following questionnaires, including patient-reported outcome measures (PROMs): the Oxford Knee Score (OKS) [21], the Knee Society Score (KSS) [22], the University of California at Los Angeles (UCLA) Activity Scale, the Numeric Rating Scale (NRS) for pain [23] and the Short Form 12 Questionnaire (SF-12) [24].

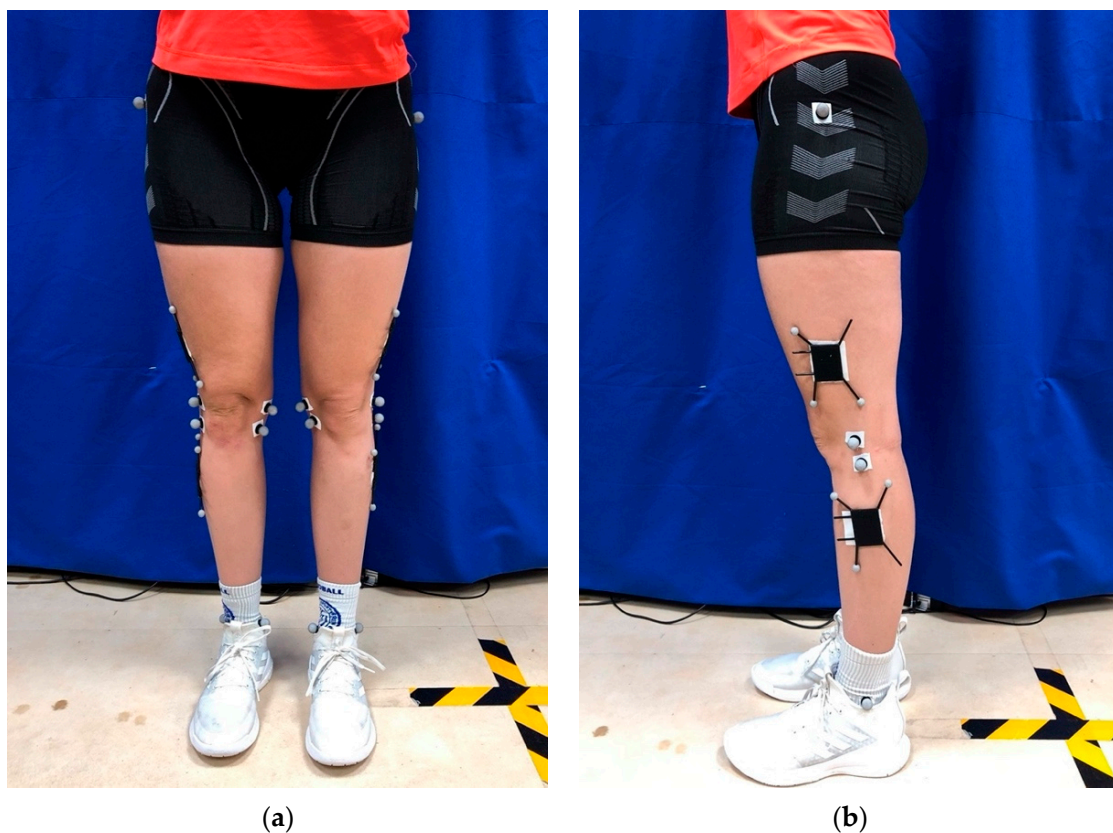
## 2.3. Recruitment and Inclusion Criteria

Inclusion criteria for the MOA group consisted of severe unilateral osteoarthritis of the medial compartment classified using the Kellgren–Lawrence classification [25] or the Ahlbäck classification [26] with full-thickness articular cartilage loss (‘bone on bone’). In all patients in the preoperative examination, the anterior cruciate ligament and the medial and lateral collateral ligaments were functionally intact, the valgus deformity was manually correctable and there was no evidence of OA in the lateral knee compartment. Rheumatoid arthritis, fixed valgus deformity (e.g.,  $>15^\circ$ ), flexion deformity  $> 15^\circ$ , or the inability to walk 6 min without an assistive device was considered a contraindication. The control

group consisted of young and healthy subjects. Excluded were participants with prior knee surgery and functional limitations in the knee.

#### 2.4. Motion Analysis

To evaluate kinematic joint parameters, spatiotemporal parameters were collected, and femorotibial translation and gait analysis were performed using the OptiTrack 3D motion analysis system (NaturalPoint Inc., Corvallis, OR, USA) with a recording frequency of 100 Hz and the “705 CST Proform” treadmill. Thirteen reflective markers were attached with adhesive tape to anatomical landmarks on each leg [27] (Figure 2). The recordings were managed using ‘Capture2D™’ (v1.0.0.194, C-Motion Inc., Boyds, MD, USA) [20]. A lowpass Butterworth filter with a threshold of 6 Hz of the first order was applied to process and analyse the recorded data, and missing data were interpolated up to 10 frames using Visual 3D Professional™ (v1.0.0.194, C-Motion Inc., Boyds, MD, USA). All participants walked forward and were recorded for 30 s.



**Figure 2.** Reflecting markers used for gait analysis: (a) frontal view; (b) sagittal view.

#### 2.5. Motion Assessment

Prior to recording gait and running analyses, an acceleration-based functional calibration procedure was performed each time. Participants began walking on the treadmill at a self-selected speed. Participants had a six-minute period of habituation to walking on the treadmill to rule out bias due to altered gait pattern [28].

After a comfortable walking speed was established, the investigator recorded at least 23 walking cycles on the treadmill after signalling the participant. Spatiotemporal motion parameters, as well as the ROM in all three axes, were recorded per participant. In all recordings, the used marker system had a residual of 1.2 mm.

### 2.6. Statistical Analysis

Statistical analysis was performed by using Jamovi for Windows (The Jamovi project (2022), Version 2.2.5, [www.jamovi.org](http://www.jamovi.org) accessed on 7 May 2023). For normal distribution, the Shapiro–Wilk test was performed. The Student’s *t*-test and the Mann–Whitney U-test were used to test for statistical significance. The significance level was defined as  $p < 0.05$ . For multiple testing, the Bonferroni correction was applied [29].

## 3. Results

### 3.1. In Vitro Analysis

The ROM of the tibial marker in the loading response phase of the gait cycle is shown in Table 1. The collected results vary when artificial ligament tension is applied or the inlay is removed.

**Table 1.** Range of the femorotibial translation in the artificial model of a knee. Values are given as mean  $\pm$  standard deviation (SD).

Range of Motion	Medio–Lateral	Anterior–Posterior	Cranio–Caudal
mean $\pm$ SD [mm]	2.05 $\pm$ 1.05	2.25 $\pm$ 0.55	2.18 $\pm$ 0.57
inlay–/strings+	1.11	1.58	1.34
inlay–/strings–	3.14	2.31	2.43
inlay+/strings+	1.21	2.92	2.47
inlay+/strings–	2.75	2.21	2.50

### 3.2. Case–Control Study

A total of 40 participants were included in the study. The MOA group consisted of 11 patients (3 women, 8 men) with severe MOA scheduled for unicompartmental knee replacement surgery. The control group contained 29 healthy participants (16 women, 13 men). Demographic data are shown in Table 2.

**Table 2.** Demographics of the participants. Values as mean  $\pm$  standard deviation (SD).

Parameters	Control Group	MOA Group
age [years]	22.07 $\pm$ 2.23	68.73 $\pm$ 9.22
height [cm]	175.76 $\pm$ 7.79	179.27 $\pm$ 7.96
weight [kg]	69.91 $\pm$ 12.43	88.27 $\pm$ 17.75
BMI <sup>1</sup> [kg/m <sup>2</sup> ]	22.5 $\pm$ 2.83	27.52 $\pm$ 5.59

<sup>1</sup> Body mass index.

The MOA group showed significant differences in the KSS ( $p < 0.001$ ), OKS ( $p < 0.001$ ), UCLA Activity Scale ( $p < 0.001$ ), NRS for pain ( $p < 0.001$ ) and SF-12 Physical Component Summary (PCS) ( $p < 0.001$ ) to the controls. The SF-12 Mental Component Summary (MCS) showed no significant differences ( $p = 0.785$ ). The absolute values are shown in Table 3.

**Table 3.** Scores of the participants in the case–control study. Values are given as mean  $\pm$  SD.

Scores [Range]	Control Group	MOA Group	<i>p</i> -Value
KSS <sup>1</sup> [0–200]	195.5 $\pm$ 8.38	126.73 $\pm$ 42.54	<0.001
OKS <sup>2</sup> [12–60]	12.20 $\pm$ 0.95	31.40 $\pm$ 4.92	<0.001
UCLAAS <sup>3</sup> [1–10]	9.66 $\pm$ 1.04	6.36 $\pm$ 1.03	<0.001
NRS <sup>4</sup> [0–10]	0.35 $\pm$ 0.90	5.36 $\pm$ 1.86	<0.001
SF-12 PCS <sup>5</sup>	56.80 $\pm$ 2.37	38.6 $\pm$ 8.48	<0.001
SF-12 MCS <sup>6</sup>	54.20 $\pm$ 6.94	54.10 $\pm$ 10.40	0.785

<sup>1</sup> Knee Society Score. <sup>2</sup> Oxford Knee Score. <sup>3</sup> UCLA Activity Scale. <sup>4</sup> Numeric Rating Scale. <sup>5</sup> Short Form 12-Item Health Survey Physical Component Summary. <sup>6</sup> Short Form 12-Item Health Survey Mental Component Summary.



The spatiotemporal parameters of the MOA group showed a significant reduction in speed ( $1.23 \pm 0.16$  m/s vs.  $0.86 \pm 0.31$  m/s,  $p < 0.001$ ) and stride length ( $1.4 \pm 0.16$  m vs.  $1.0 \pm 0.28$  m,  $p < 0.001$ ) compared to the control group (Table 4). Stride frequency was not significantly different ( $105.0 \pm 6.5$  steps/min vs.  $99.0 \pm 15.9$  steps/min,  $p = 0.074$ ). The ROM for flexion significantly decreased throughout the gait cycle for both legs ( $p < 0.001$ ). Loading response changes in flexion differences were not statistically significant ( $p = 0.074$  left,  $p = 0.096$  right). The differences in ROM for abduction/adduction were not significant.

**Table 4.** Spatiotemporal and kinematic parameters in the case–control study.

Parameters	Side	Control Group	MOA Group	p-Value
velocity [m/s]		$1.23 \pm 0.16$	$0.86 \pm 0.31$	$<0.01^{*,1}$
cadence [1/min]		$105.00 \pm 6.50$	$99.00 \pm 15.9$	$0.07^1$
stride length [m]		$1.40 \pm 0.16$	$1.02 \pm 0.28$	$<0.01^{*,1}$
ROM flexion [°] full gait cycle	left	$62.57 \pm 6.99$	$50.00 \pm 7.61$	$<0.01^{*,1}$
	right	$62.58 \pm 6.32$	$52.40 \pm 6.58$	$<0.01^{*,1}$
ROM flexion [°] loading response	left	$9.34 \pm 3.81$	$7.10 \pm 7.659$	$0.07^2$
	right	$12.35 \pm 4.43$	$10.50 \pm 8.95$	$0.09^2$
ROM ab-/adduction [°] full gait cycle	left	$12.03 \pm 3.97$	$9.16 \pm 2.90$	$0.04^1$
	right	$11.74 \pm 4.03$	$8.24 \pm 2.99$	$0.01^1$
ROM ab-/adduction [°] loading response	left	$3.78 \pm 1.89$	$2.59 \pm 1.50$	$0.07^2$
	right	$3.57 \pm 1.46$	$3.00 \pm 1.82$	$0.18^2$

Mean  $\pm$  standard deviation, ROM = range of motion, \* statistical significance, <sup>1</sup> Student's *t*-test, <sup>2</sup> Mann–Whitney U-test.

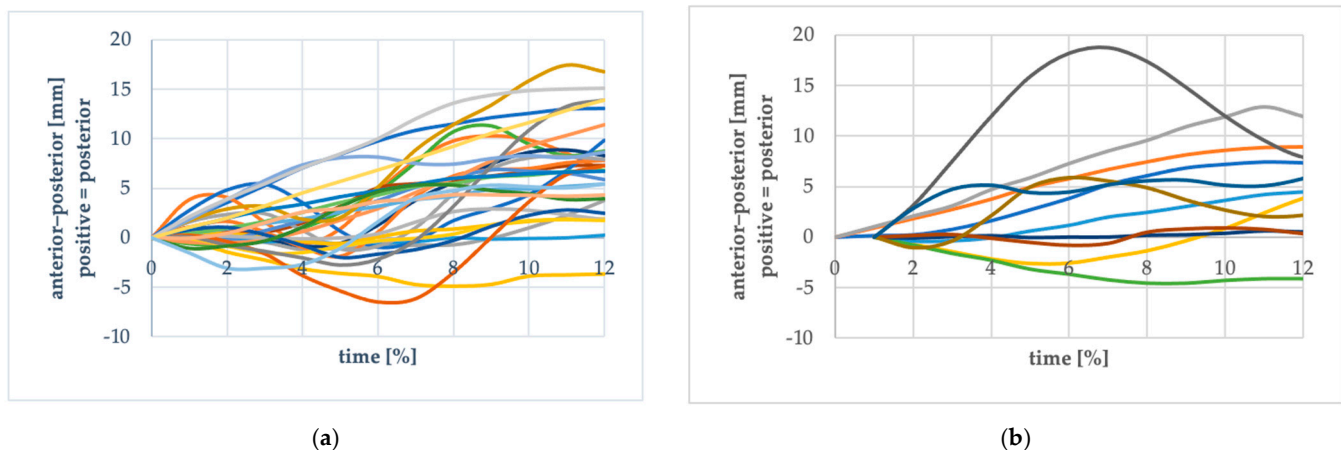
Femorotibial translation in the loading phase was not significantly different between the MOA group and the control group (Table 5). The 4% gait cycle time shift was applied to the data prior to analysis.

**Table 5.** Femorotibial translation in the loading response.

Axis	Side	Control Group	MOA Group	p-Value
medio–lateral [mm]	left	$5.2 \pm 2.9$	$4.1 \pm 2.6$	$0.27^1$
	right	$6.6 \pm 4.5$	$4.6 \pm 3.6$	$0.18^2$
anterior–posterior [mm]	left	$8.6 \pm 4.4$	$7.4 \pm 5.0$	$0.46^1$
	right	$8.6 \pm 5.3$	$9.7 \pm 7.5$	$0.79^2$
cranio–caudal [mm]	left	$2.6 \pm 1.5$	$3.5 \pm 2.8$	$0.16^1$
	right	$4.5 \pm 2.4$	$5.1 \pm 3.6$	$0.56^1$

Mean  $\pm$  SD, <sup>1</sup> Student's *t*-test, <sup>2</sup> Mann–Whitney U-test.

Differences between the patients' legs were considered. In the medio–lateral axis, translation was  $3.2 \pm 2.0$  mm in the diseased limb and  $5.5 \pm 3.6$  mm in the healthy limb ( $p = 0.065$ ). Anterior–posterior translation was  $8.2 \pm 3.6$  mm (diseased limb) and  $9.0 \pm 8.4$  mm (healthy limb) ( $p = 0.562$ ). For superior–inferior, translation was  $3.5 \pm 2.3$  mm (diseased limb) and  $5.2 \pm 3.9$  mm (healthy limb) ( $p = 0.401$ ). The intraindividual comparison showed no statistically significant differences. A large intraindividual variation of femorotibial translation in the anterior–posterior plane is exemplarily shown in Figure 3.



**Figure 3.** Femorotibial translation in the loading response phase (first 12% of the gait cycle) in the anterior–posterior plane of the case–control study: (a) control group; (b) MOA group.

#### 4. Discussion

OA is one of the most common causes of painful loss of mobility in many populations [30,31]. Biological, mechanical and structural components are associated with OA as a disease of the whole joint [2]. An interplay of metabolic and mechanical changes and changes in the levels of inflammatory cytokines [6] leads to an overall change in the kinematics of the joint as an expression of the clinical progression of OA. As the severity of OA corresponds with the expression of kinematic changes [14], the timing of diagnosis and intervention is essential for patients' outcomes [2].

Gait analysis can be used to identify functional changes in knee kinematics in patients with KOA. Decreased knee flexion and prolonged heel strike during the loading response phase of the gait cycle are signs of early OA [8]. The methodical approach carried out in this study demonstrates that small decreases in ligament tension result in a higher femorotibial translation during the loading response phase as a possible indicator and early sign of changed knee kinematics in OA resulting in mechanical changes (Figure 3).

To prove that increased femorotibial translation is present in patients with serious KOA and can be substantiated by 3D gait analysis and demonstrated among other typical KOA changes, we carried out a field trial using a treadmill algorithm and a marker-based analytic system [32]. Our experimental design was confirmed by multiple recordings, resulting in a low variance of data. In recent years, markerless motion analysis methods and interactive measurement systems have been gaining ground. The integration of artificial intelligence into motion analysis opens up the possibility of performing motion analysis with less data acquisition and processing time compared to marker-based methods [33]. Nevertheless, we chose to record the gait of patients with KOA using a marker-based system because the determination of joint centres and joint angles with a markerless system is not yet accurate enough for clinical applications.

The results of this study demonstrate and confirm osteoarthritic changes in severe unicompartmental medial OA gait [15]. Significant changes in spatiotemporal and kinematic parameters typical of patients with MOA were found. These included reduced speed, reduced stride length and reduced ROM of knee flexion [8–13]. Differences in cadence and stride length and ROM of abduction/adduction were not statistically significant. Recent studies have demonstrated gait abnormalities in osteoarthritic joints using markerless 3D gait analysis and wearable sensors [34,35]. Boekesteijn (et al.) (2022) showed spatiotemporal changes and compensatory mechanisms typical of OA and were able to objectively assess the gait pattern using an inertial measurement system in a clinical setting. Wang (et al.) (2024) found the amount of knee flexion during inline lunging to be another potential indicator of knee osteoarthritis using a markerless motion capture system [35].

When looking at PROMs, our cohort displays differences from the control group in all scores specific to knee function, confirming that our MOA cohort had significantly worse knee function and physical health. MOA patients did not show any impairments regarding their mental health despite their advanced KOA. Overall, our MOA cohort was representative of patients with KOA [36].

The hypothesis that an osteoarthritic knee would have a greater femorotibial translation than an unaffected knee was not confirmed. Our study design may have led to group effects due to significant differences in demographics (age, weight, BMI). Increasing age influences the spatiotemporal parameters of gait, as ageing leads to reduced joint mobility and a decrease in muscle mass. Increased weight, and consequently increased BMI, increases joint loading and ground reaction forces, which can lead to altered gait patterns in people with higher BMI. When high BMI and older age are combined, their effects on gait may be exacerbated and result in a functional decline [37–39].

There were no statistically significant differences in femorotibial translation between the control and MOA groups. This is consistent with the data from Favre (et al.) (2014), who were unable to detect anterior displacement of the femur in patients with severe OA. [40]. In their study on the relationship between the Kellgren–Lawrence score and 3D kinematic gait analysis, Zeng (et al.) (2017) observed that in a Chinese population suffering from KOA, there was increased femoral translation anteriorly and distally at heel strike. In a recent study by Postolka (et al.) (2020), the authors demonstrate that the translation between the two femoral condyles and the tibia is highly task-dependent and individualised. They also state that further research is needed to clarify the role of limb alignment on knee joint kinematics, which is consistent with our findings. The study indicates that the selection of implants for arthroplasty should be individualised, taking into account the recognition of knee joint kinematics prior to surgery. This approach may facilitate further improvements in arthroplasty outcomes.

In the current study, no relevant differences between the left and right sides were identified (Table 5). It is noticeable that the scatter of the data is large in our study population. This means that there is a large interindividual variation in femorotibial translation as well, without a specific pattern being recognisable for KOA (Figure 3). Furthermore, there is no relevant difference in femorotibial translation between the healthy and diseased limbs in the MOA group. This is in contrast to a study by Zeng (et al.) (2024), which demonstrated increased femorotibial translation in ACL-deficient knees with cartilage lesions compared to ACL-deficient knees without cartilage lesions in patients with post-traumatic osteoarthritis (PTOA). These results could have significant implications for future indications for UKA or TKA and support the need for preoperative kinematic analysis in patients with MOA, especially in PTOA [7].

KOA is not limited to one limb, as previously described by Perry (1992) and Goodfellow (et al.) (2015). KOA alters mechanical and kinematic patterns in movement as a systemic disease; thus, the impaired function of one leg leads to an altered gait pattern in both legs [2,8,15].

The findings of this study must be interpreted in the context of its limitations. Treadmill walking provides controlled and repeatable conditions, yet it can alter natural gait patterns and result in slower gait speed and shorter stride length [41]. This is a bias in our study that must be taken into account when interpreting the results. Skin markers were used to record the movements; however, marker placement is known to be able to bias data. In our recordings, the used marker system had a residual of 1.2 mm, which led to uncertainty. This problem is present in any marker-based motion capture system and cannot be excluded. Therefore, this inaccuracy of 1.2 mm of the femorotibial translation could have caused bias and defaulted into no significant variances between healthy and unhealthy joints. Thirdly, the number of participants was limited to  $n = 40$ , and the groups were not age-matched. We understand that the groups are difficult to compare, but the goal was to record a healthy knee and compare it with severe OA of the knee; therefore, we decided to include young and healthy participants in the control group despite the age differences and possible bias.



## 5. Conclusions

The current results corroborate the typical changes observed in PROMs, as well as the spatiotemporal and kinematic results associated with MOA, as evidenced by the gait changes typically observed in patients with KOA. However, clinical gait analyses revealed no significant difference in femorotibial translation during the loading response phase of stance. The extent of individual femorotibial translation may prove to be an important parameter for altered joint kinematics in patients with MOA, especially prior to UKA implantation. In the future, the extent of femorotibial translation may provide valuable information for the diagnosis, treatment and monitoring of MOA.

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