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Weight-bearing radiography depends on limb loading

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Abstract

Purpose The mechanical axis of the lower limb has shown to vary between different weight-bearing conditions and change after total knee arthroplasty (TKA). The purpose of this study was to investigate the correlation between mechanical axis alignment in standing long-leg radiographs and limb loading after TKA.

Methods Mechanical axis of the lower limb and limb loading have been prospectively evaluated in 115 patients 10 days and 3 months after TKA. By the moment of standing long-leg radiography for analysis of the mechanical leg axis, two digital scales separately captured the load of each limb.

Results Mechanical axis changed from an initial $-1° \pm 2°$ valgus alignment to a varus axis of $+1° \pm 2°$ ($p < 0.01$). This change in alignment was associated with an increase of limb loading from 89.9 ± 10.7 to $93.0 \pm 7.0\%$ ($p < 0.01$). The mechanical axis strongly correlated with relative limb loading at the first and second measurements ($r = 0.804$, $p < 0.001$, respectively, $r = 0.562$, $p < 0.001$). A significant change in the rate of outliers was registered within the observation period. These alterations and distinctions were much more pronounced in patients with postoperative incomplete extension ($n = 15$).

Conclusions The postoperative mechanical axis correlates with limb loading. A clinical relevant change in frontal alignment of the lower limb is associated with increased limb loading after TKA. The actual mechanical axis can only be assessed at physiological limb loading in long-leg radiographs with complete extension at full weight bearing.

Level of evidence Diagnostic study, Level II.

Keywords Total knee arthroplasty · Total knee replacement · Mechanical axis · Limb loading · Standing long-leg radiographs

Abbreviations

BMI	Body mass index
TKA	Total knee arthroplasty
NRS	Numerical rating scale

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Introduction

The frontal alignment of the lower limb determines the load distribution of the knee [7]. Mechanical leg axis is thought to be important in the evolution of osteoarthritis [41]. A neutral mechanical axis with an acceptable range of 3° in axis deviation is considered as optimal alignment, and supposed to influence function and survival rates after TKA [2, 8, 30, 31, 47]. The axis alignment of the lower limb can be reliably measured in standing long-leg radiographs [5, 9, 37]. Different factors affecting the accuracy of the mechanical axis measured in long-leg radiographs have been identified including position of the leg with rotation or knee flexion [17, 21, 26, 28, 38]. Correct radiographic technique is, therefore, essential for the measurement.

Mechanical axis alignment has been supposed to be affected by different weight-bearing conditions. A significant difference of the mechanical axis between weight-bearing and non-weight-bearing radiographs has been reported [13, 14, 35, 36, 39]. A clinical relevant change of the radiological mechanical axis within the first 3 months after TKA was assumed to depend on limb loading [53]. The underlying mechanism for the change in mechanical axis alignment has not yet been determined. Muscle activation and forces have shown to be reduced after TKA and non-physiological weight bearing may have an effect on the measurement of the mechanical axis [35, 49, 50, 52]. Limb loading could influence the mechanical axis alignment of the lower limb measured in standing long-leg radiographs.

The purpose of this study was to investigate the mechanical axis in relation to limb loading after TKA. A correlation between weight-bearing radiography and loading of the lower limb was hypothesised. The underlying mechanism of the variation of the mechanical axis alignment between different weight-bearing conditions and the change of after TKA would be revealed. A significant different distribution of outliers would indicate the clinical relevance of the findings.

Materials and methods

This study prospectively investigated a consecutive series of 115 TKAs in 115 patients with primary osteoarthritis (Table 1). Exclusion criteria were a preoperative extension deficit > 20°, a valgus or varus malalignment > 15° and previous surgery of the affected joint (Fig. 1). Between December 2014 and September 2015, 115 TKAs (Journey Bicruciate Substituting Knees, Smith & Nephew, Memphis, TN, USA) without retropatellar replacement were implanted with patient-specific instrumentation (Visionaire$^{®}$, Smith & Nephew, Memphis, TN) via a medial parapatellar approach under general anaesthesia [37]. The preoperative planning consisted of a neutral mechanical axis. Planning of the implant position was done in the MRI's frontal plane and perpendicular to the mechanical femoral and tibial axes [53]. Rotation of the femoral component was adjusted by the gap-balancing method around the transepicondylar axis [15]. Posterior tibial slope was set to 3° [15].

All included 115 patients were available at the follow-up at 10 days (range 7 to 12 postoperative day) and 3 months postoperative (Fig. 1). Demographic data (sex, age, weight, height), date of surgery and follow-up were recorded for each patient.

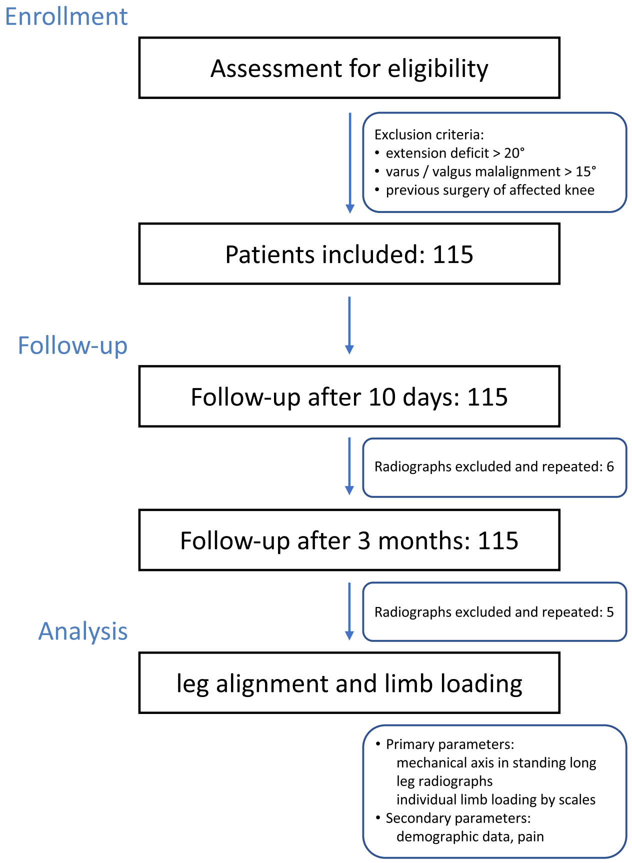

Fig. 1 Flow diagram with the number of patients enrolled and analysed

Mechanical axis of the lower limb was determined by performing a standardised long-leg radiograph (Centricity Enterprise Web 3.0; GE Healthcare Pty Ltd, Piscataway, NJ, USA) as previously described [2, 53]. Anterior–posterior, long-leg radiographs with the radiographic beam centred to the joint line were taken with the patients standing with feet at shoulder width, equally distributed weight bearing and patella pointing straight forward at maximum knee extension

Table 1 Preoperative data of the study cohort

Patients	All	Knee extension at 10 days after TKA	
		Complete	Incomplete
n	115	100	15
Age (years)	69.5 ± 7.9 (49 to 85)	69.6 ± 7.8 (53 to 85)	68.8 ± 8.4 (49 to 81)
Female:male	71:44	61:39	10:5
Body weight (kg)	86 ± 11 (56 to 115)	85 ± 11 (56 to 110)	94 ± 10 (72 to 115)
BMI (kg/m^2)	29.3 ± 2.7 (23.3 to 36.6)	29.2 ± 2.8 (23.3 to 36.6)	29.9 ± 2.7 (25.2 to 35.4)
Mechanical axis (°)	5 ± 5 (− 7 to 15)	5 ± 5 (− 7 to 15)	5 ± 6 (− 5 to 14)

Values are expressed as mean, with standard deviation and range, respectively, as ratio for gender

[53]. The digitally processed radiographs were obtained in one exposure with a tube-to-plate distance of 2 m on an imaging plate measuring 354 × 1245 mm, at 80–90 kV and 63–100 mA depending on body mass index [5, 9, 53]. Radiographs were only accepted for further analysis if the requirements were fully implemented: central patellar tracking, coverage of the fibular head by the tibia ($^2/_3$; $^1/_3$), position of the ankle, neutral rotation of the leg with correct visualisation and projection of the trochanter minor [13, 19, 38].

Mechanical axis was analysed as previously described [13, 34, 39, 53]. A varus axis was indexed in the case of positive angles and a valgus axis in the case of negative angles. Limb loading of each leg was assessed using two scales while performing the long-leg radiograph in accordance with a previously described method [16]. Each scale was securely mounted to the ground at the same level and calibrated by using known weights. The patient was asked to distribute the weight as evenly as possible between the two legs while looking directly ahead and stably standing still. Absolute limb loading was read off and documented in kilograms (kg), and relative limb loading was calculated relative to the equal contributed body weight. Patients were not able to see the display of the scales.

At each follow-up and radiograph, range of motion was measured using a goniometer [11, 23]. The 115 patients were differentiated into two groups: patients with complete postoperative extension to neutral position after TKA ($n = 100$) and patients with incomplete extension with a deficit of extension ranging from 5 to 15% ($n = 15$) at the time of the first postoperative radiograph (Table 1).

Pain level was assessed with a standardised Numerical Rating Scale (NRS) ranging from 0 to 10. All patients received standardised, multimodal, postoperative treatment regarding pain therapy, thromboembolic prophylaxis and physiotherapeutic regime. Full weight bearing and passive and active mobilisation were performed for all patients starting at the first postoperative day. The competent ethics committee gave approval for the study (AS 17 (bB)/2015) and an informed consent was obtained from all patients.

Statistical analysis

Parameters are presented by means, standard deviations and ranges. For statistical analysis, we used the Wilcoxon test for paired samples, the Mann–Whitney *U* test for non-paired samples and Pearson's test for correlation analysis. All radiographs were assessed by the two authors (HH, RZ). The mean correlation coefficient of interobserver reliability of all measurements was 0.966 (range: 0.955–0.974), whereas the mean correlation coefficient of intraobserver reliability was 0.959 (range: 0.946–0.969). A post hoc analysis revealed a power of > 0.8 for $n = 100$ patients with a two-tailed alpha < 0.05 for all evaluated parameters. Statistical analysis was performed using SPSS software with a level of significance set at $p < 0.05$ (SPSS version 21; SPSS Inc, Chicago, IL, USA).

Results

Patients with complete extension ($n = 100$) presented with a mechanical axis of − 1° ± 2° at the 10th day after the TKA (Fig. 2; Table 2). After 3 postoperative months, mechanical axis changed to a varus alignment of + 1° ± 2° ($p < 0.001$; Figs. 2, 3; Table 2). At the first measurement, 16 of the 100 patients had a valgus alignment of more than − 3°. Two of them continued to demonstrate an increased valgus alignment up to − 4° after 3 months and two others were found to have an increased varus alignment of 4° after 3 months compared to the neutral axis assessed before.

The change in alignment was accompanied by an increase of limb loading ($p < 0.01$). Patients assessed with a relative limb loading of at least 90% at the first measurement showed an increase of the mechanical axis from 0° ± 1° to 1.0° ± 1° ($n = 72$). This difference was significantly larger ($p < 0.001$) in patients with an initial loading below 90% as initially calculated with − 3° ± 0° and 0° ± 2° in the second radiograph ($n = 28$).

Mechanical axis was strongly correlated with relative limb loading at the first ($r = 0.804$, $p < 0.001$; Fig. 4) and second measurement ($r = 0.562$, $p < 0.001$). Mechanical axis also correlated with a minor manifestation with absolute limb loading at both measurements ($r = 0.581$, $p < 0.001$, respectively, $r = 0.27$, $p < 0.01$).

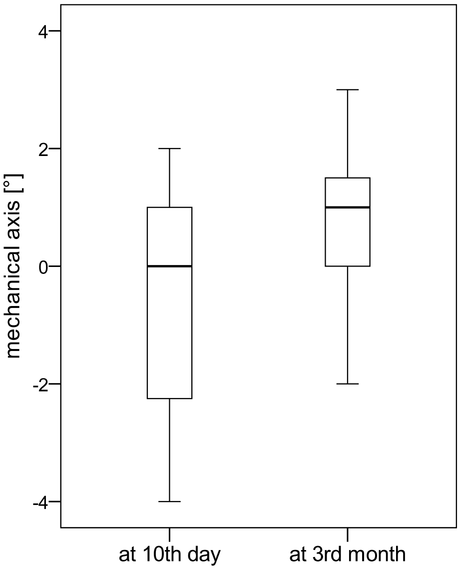

Fig. 2 Changes of mechanical axis between 10 days and 3 months after TKA in patients with initial complete extension ($p < 0.001$)

Table 2 Mechanical axis alignment, limb loading and pain levels at 10 days and 3 months after TKA in patients with complete extension

$N = 100$	10th postoperative day	3rd postoperative month	p
Mechanical axis (°)	-1 ± 2 (-4 to 2)	1 ± 1 (-4 to 4)	< 0.001
Relative limb loading (%)	89.9 ± 10.7 (65 to 100)	93.0 ± 7.0 (65 to 100)	< 0.01
Absolute limb loading (kg)	38.3 ± 6.9 (23 to 55)	39.7 ± 6.1 (27 to 55)	< 0.01
NAS	3 ± 1 (1 to 5)	1 ± 1 (0 to 4)	< 0.001

Values are expressed as mean, with standard deviation and range

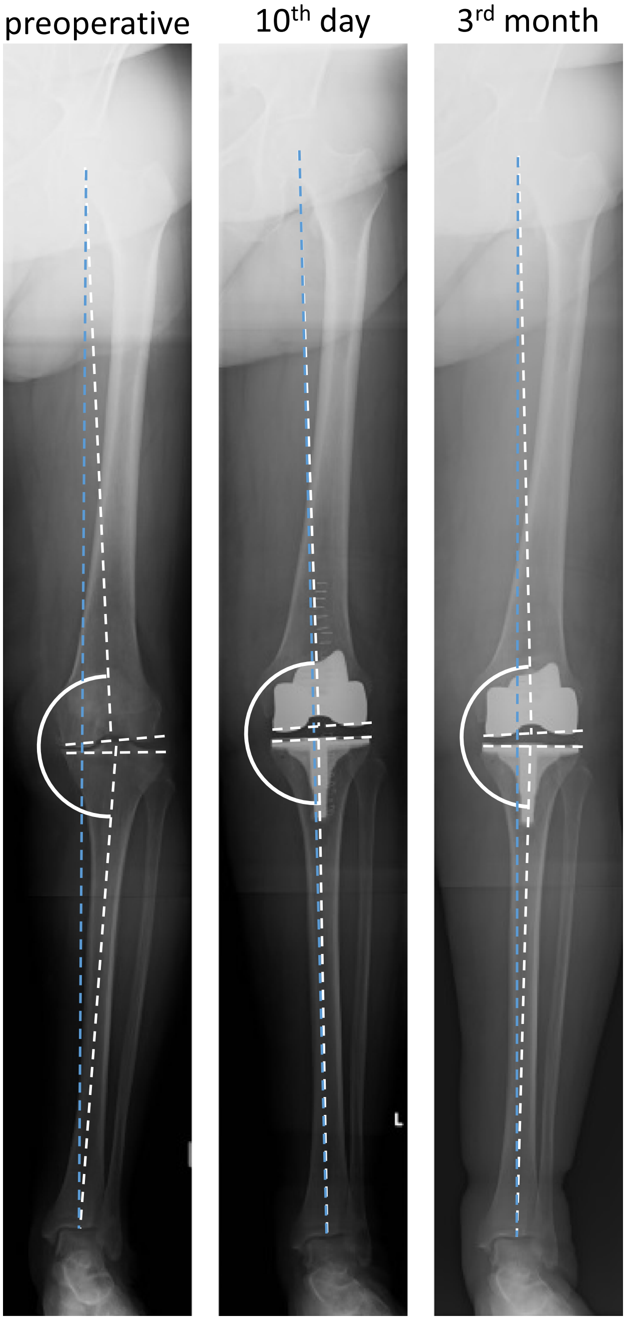

Fig. 3 Representative illustration of change in mechanical axis alignment measured at the different time points after TKA

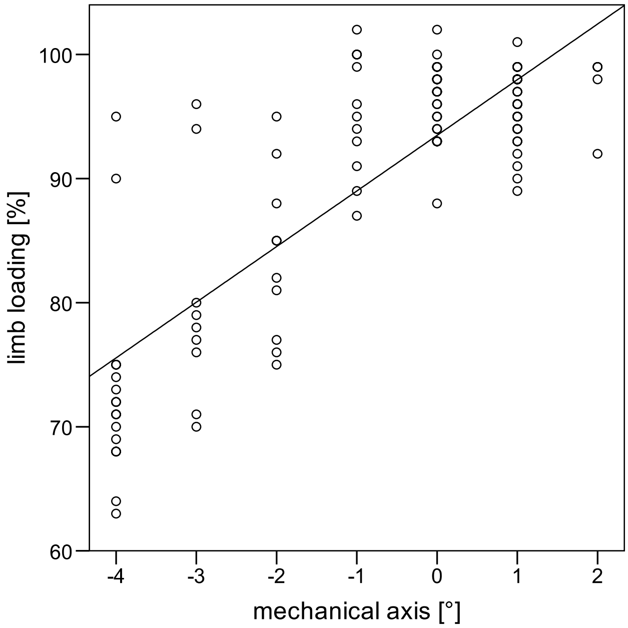

Fig. 4 Correlation of relative limb loading and mechanical axis alignment at 10 days after TKA ($y = 93.49 + 4.48 \times X$; $R^2 = 0.656$)

Pain levels measured by NRS decreased during the postoperative observation time ($p < 0.001$). There was no significant correlation between pain levels, BMI or body weight with the mechanical axis or relative limb loading.

In the 15 patients with incomplete extension, the initial axis was assessed with a valgus of -3 ± 1 (range $-5°$ valgus to $-1°$ valgus) and showed a change to a valgus axis of -1 ± 2 (range $-4°$ valgus to 2° varus) at the second measurement ($p < 0.001$). Relative limb loading increased from 66.3 ± 6.7 to $87.3\% \pm 11.3\%$ ($p < 0.001$) and absolute limb loading from 31 ± 4 to 41 ± 8 kg ($p < 0.001$) during the observation period. Pain levels simultaneously decreased from 4 ± 1 to 1 ± 1 ($p < 0.01$). The mechanical axis in both radiographs differed between patients with complete extension compared to those with incomplete extension ($p < 0.001$ and $p < 0.01$, respectively, Fig. 5). Absolute and relative loading showed a subgroup specific difference at the first measurement ($p < 0.001$, each). Significant differences were found between these two groups for body weight ($p < 0.01$)—not for BMI—and pain levels at both assessments ($p < 0.01$ and $p < 0.05$, respectively).

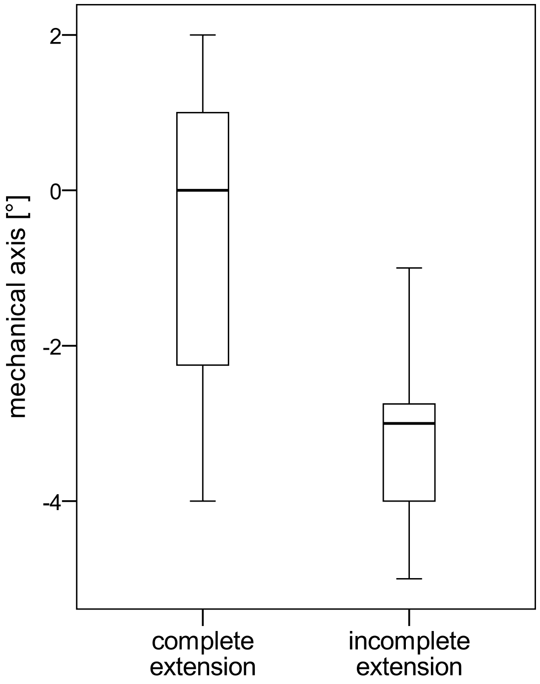

Fig. 5 Difference of mechanical axis in patients with complete extension compared to patients with incomplete extension at 10 days after TKA ($p < 0.001$)

Discussion

The most important finding of the present study was the correlation beween mechanical axis of the leg and limb loading after TKA, which was observed for the first time. Weight-bearing radiography strongly correlated with limb loading and the mechanical axis of the lower limb was dependent on limb loading.

The findings reflect the influence of individual physiological limb loading on mechanical axis alignment with its adaption on weight bearing and rebalancing within the first months after TKA. These processes may include adaptive alterations of soft tissue with ligaments, capsule of the knee joint and muscular interactions, which even may exist with an intraoperative gap-balancing method or kinematic alignment [4, 10, 15, 24, 25, 42, 48]. It has been previously demonstrated that the mechanical axis was comparably affected by different weight-bearing conditions before and after high tibial osteotomy and TKA [6, 35, 39, 40, 45, 51].

The second main finding of this study is that limb loading immediately after TKA is often reduced, even though direct postoperative full weight bearing would be technically possible [3]. Pain levels simultaneously decreased within the observation time, which indicates a likely pain-related component of reduced postoperative limb loading despite potent analgesia.

The results of alignment analysis agree with those of a different study with a distinct study cohort [53]. In the actual study, 14% of patients would falsely be considered as malaligned in the first measurement. Outliers could only be verified in 4% after 3 months, indeed. The shift in the rate of outliers within the first 3 months after TKA indicates the clinical relevance of the findings. Immediate postoperative standing long-leg radiographs are not able to assess the actual mechanical axis alignment, when limb loading is reduced.

Patients with incomplete extension showed a significant different axis alignment, limb loading and more distinct changes compared to patients with complete extension, which highlights the impact of limb loading. Body weight seems to influence the function after TKA, as the subgroup analysis (see Table 1) and previous studies revealed [12]. This information is limited by the small number of patients with postoperative incomplete extension.

The follow-up of the actual study was limited to 3 months due to no further observed changes in mechanical axis between 3 and 12 postoperative months in a previous study [53]. Changes over a longer time period could exist and depend on different loading scenarios, especially at high body weight. Subsequent studies could investigate the effects of different loading scenarios on function and survival time after TKA [43]. Static weight bearing, which was analysed in the actual and previous studies, may not reflect the conditions of physiologic dynamic loading during walking, which could even be more important for a functional analysis [33, 48].

The accuracy of the evaluation is warranted and limited by the precision of the method [5, 9, 20]. Standing long-leg radiographs have been shown to reliably detect differences of few degrees in several studies investigating the accuracy of mechanical axis alignment [18, 32, 35, 37]. Differences and changes of mechanical axis alignment to the extent evaluated in the actual study are statistically significant and clinically relevant [1, 2, 7, 8, 27, 37, 38]. However, the effect of a minor increase in weight bearing may be enhanced by further loading depending interactions [3, 29, 49]. Additional weight-bearing independent factors may even exist and influence the measurement of mechanical axis alignment [22, 44].Even if computed tomography has a higher accuracy in determination of axis alignment, standing long-leg radiographs represent the only routine radiographic technique under weight-bearing condition [46].

Exact limb loading was measured with a digital device, which did not change the standardised procedure of long-leg radiography. Patients were not able to visualise the weight by themselves, so any influences of the limb loading assessment on the radiography may be considered as excluded.

Conclusions

Mechanical alignment of the leg correlates with limb loading. Only at physiological loading with full weight bearing and complete knee extension, long-leg radiographs reflect the true mechanical axis of the lower limb.

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Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest.

Ethical approval This study was approved by the competent ethical committee (AS 17 (bB)/2015).

Informed consent A written informed consent was obtained from all patients.

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