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Original Research

The need for a standardized whole leg radiograph guideline: The effects of knee flexion, leg rotation, and X-ray beam height



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ABSTRACT

Introduction: Lower limb malalignment is a major risk factor for knee osteoarthritis (OA) and is mainly diagnosed using the Hip Knee Ankle Angle (HKA). Therefore, accurate HKA measurements are indispensable.

Objectives: This study aimed to research the effects of knee flexion, leg rotation, and X-ray beam height on the accuracy of the HKA measurement. To convert our findings into a guideline for obtaining whole leg radiographs (WLR) in favor of accuracy and reproducibility.

Methods: An in vitro experiment was designed using sawbones (in 5° varus) of the whole lower limb, fixated in different leg rotation angles, knee flexion angles, and three different X-ray beam heights.

Results: The HKA measurement error was 1° per 20° of leg rotation without flexion ($P < .01$). When 5° of flexion was added, the HKA measurement error was 0.8° per 20° rotation ($P < .01$). With 15° knee flexion, the HKA measurement error became 4° per 20° rotation ($P < .01$). Varying X-ray beam heights of 5cm ($P = .959$) and 10 cm ($P = .967$) did not cause any significant measurement errors.

Conclusion: This study showed that leg rotation alone (without knee flexion) can lead to clinically relevant measurement errors when exceeding 9°. When there is 15° of knee flexion and 10° leg rotation the error becomes approximately 2°. Varying X-ray beam heights within a range of 10 cm does not affect the accuracy. Based on these findings, we propose guidelines for system setup and patient positioning during a WLR that is easy to apply and aims at minimizing errors when measuring the HKA.

Introduction

Osteoarthritis (OA) is a common and disabling condition, with worldwide estimates suggesting that 500 million people are currently affected.¹ OA is a multifactorial joint disorder, associated with changes to all tissues in the knee joint, causing pain, stiffness, deformity, and disability.² Malalignment of the lower limb (varus or valgus) is an important aetiology of OA. The gold standard for diagnosing malalignment is weight-bearing whole leg radiography (WLR), on which the hip knee ankle angle (HKA) can be measured.^{3,4} Leg alignment measurement must be accurate when OA patients are indicated for either total knee arthroplasty or osteotomy.^{5,6} Therefore, WLRs must be reliable for optimal patient care.⁵

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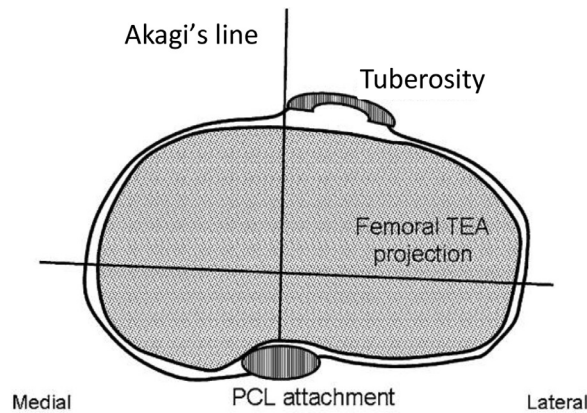


Fig. 1. Akagi line runs from the centre of the posterior cruciate ligament (PCL) insertion to the medial border of the tuberosity. The femoral transepicondylar (TEA) is projected on the tibial surface.²⁵

Patient positioning during WLRs is an inducer of HKA measurement errors. The known factors are knee flexion and extension, foot rotation, hip rotation, weight-bearing, and foot positioning.⁷⁻¹³ Multiple WLR protocols have been suggested, the one by Paley and Herzenberg being the most popular.^{4,5,14,15} In this protocol lower limbs of patients are positioned in the anteroposterior (AP) plane using the patellae as key landmarks. The X-ray technician must point a slightly convex patella bone straightforward.^{5,16} As patellar malalignment is quite common in cases of arthritic knees with a varus malalignment, HKA measurement based on the patella position can be biased.¹⁷ Other important aspects such as upper body positioning and patient instructions (foot positioning and weight-bearing) are not described by the protocol.⁵ This method is even more difficult after total knee arthroplasties, with reported HKA measurement errors up to 3.5°.^{14,18} In addition to patient positioning, the height of the X-ray beam can also impact HKA accuracy.²⁰ Katsui et al reported error in malleolar angles could be up to 2.4° when the projection angle differed 10°.²¹

There is little evidence on the test-retest reproducibility of obtaining WLRs. Odenbring et al performed a test-retest study of the measured HKA on a very small scale including 8 lower limbs, with a mean difference of 1.3°.¹⁹ Even this group made use of a meticulous method to determine the AP plane in every individual, by obtaining a lateral radiograph where the posterior aspects of the femoral condyles should be superimposed.¹⁹

Inaccurate HKA measurements caused by the lack of standardization can result in misdiagnosis, inaccurate preoperative planning, and erroneous assessment of achieved surgical corrections. The radiographic technique should be consistent and accurate, with the desired accuracy of 0.45°, reported by Jones et al as the needed wedge accuracy to achieve target corrections in high tibial osteotomy.²²

Therefore, the purpose of the current study is to find the effects of leg rotation, knee flexion and different X-ray beam heights on the measured HKA. These results can be used to improve current guidelines for obtaining WLRs with improved accuracy and reproducibility of the measured HKA.

Material and methods

Materials

Solid foam sawbones (Sawbones Europe AB, Malmoe, Sweden) of a left leg including 1 femur, tibia, fibula, talus, calcaneus, and forefoot were used. The model had a mean femoral anteversion of 15° and tibiofibular torsion of 30°.^{23,24} Metal spheres of 4 mm were placed in the femoral head, tibial spines, and talus representing the landmarks for HKA measurement to ensure reproducible image analysis. Two Kirschner wires were implanted in the tibia and femur representing the Akagi line and transepicondylar line (Fig. 1) and were used as landmarks for the AP plane.²⁵ An Ilizarov frameset fixated the sawbones in a predetermined position, in such a way that the HKA was 5° varus and the knee flexion could be adjusted between 0 and 15°.²⁶ Knee flexion was added by tilting the femur backwards in the sagittal plane, while the tibia bone stayed upright. The setup is illustrated in Fig. 2.

Radiography system

This study used a Philips DigitalDiagnost v4.0, with a fixed X-ray beam height during acquisition where the source pivoted and aimed towards the upper, middle, and lower parts of the limb. The fixed distance between the detector plate and X-ray beam source was set to 265 cm. The X-ray settings were equal to the protocol for scanning patients with kV set at 81 and varying mAs. The radiographic system contained a laser pointer (at the X-ray beam source) directed to the lead measurement tape indicating the X-ray beam height.

First, a reference radiograph as shown in Fig. 3 was made with the sawbone model set to 5° varus, 0° leg rotation, and 0° knee flexion, with X-ray beam height centred on the joint space. From this reference position, different combinations of leg-rotation (−10°,

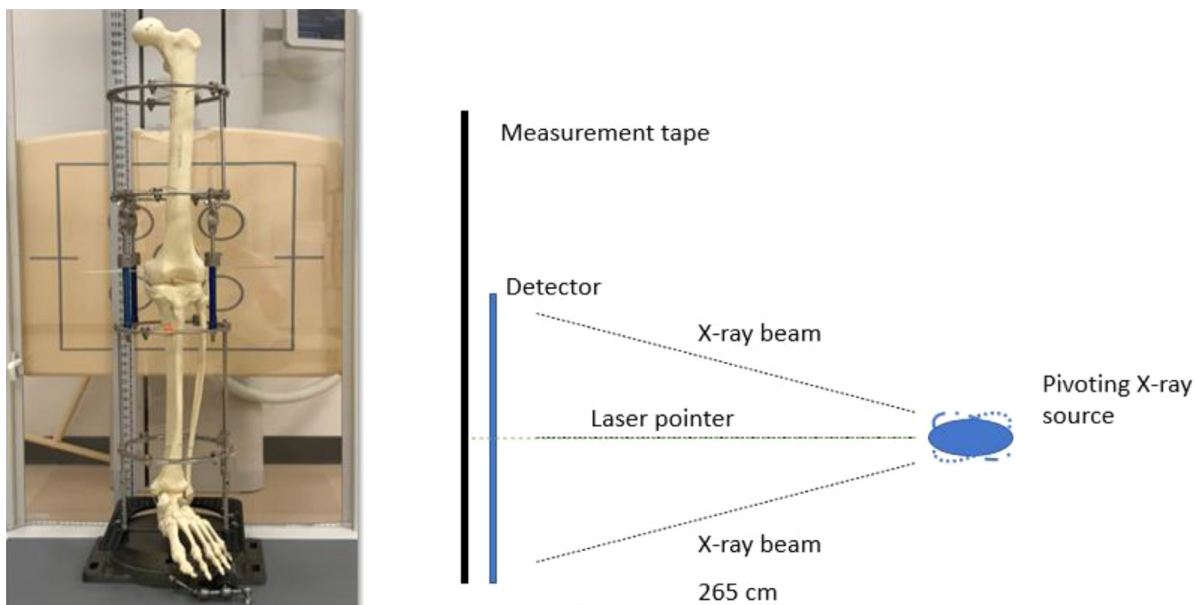


Fig. 2. Measurement setup in the projection radiography room.

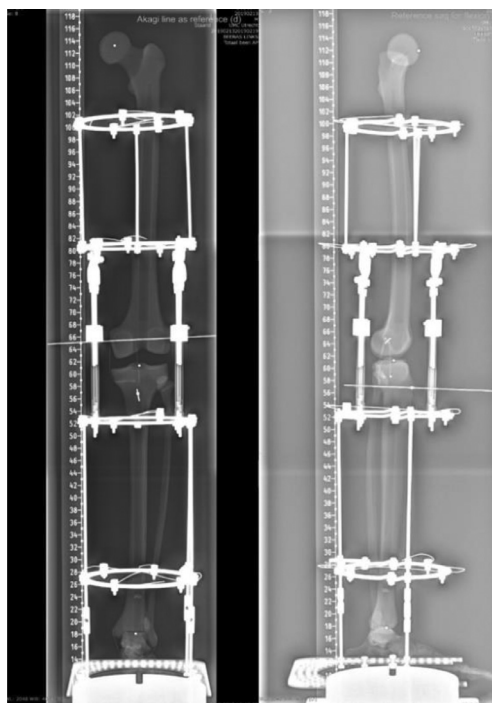


Fig. 3. Whole leg radiographs exported from PACS image viewer, with the sawbones in 5° varus and 0° knee flexion. Left image illustrates the setup in AP (anteroposterior) direction and right illustrates the image in lateral view.

5°, 0°, 5°, 10°), knee flexion (0°, 5°, 15°) and X-ray beam height (0 cm, 5 cm, 10 cm) were applied. Rotation of the leg was described as positive (external) and negative values (internal).

Angle measurement

HKAs were measured with one decimal place, using PACS IDS7 19.3 (Sectra AB, Linköping, Sweden) by annotating the metal spheres in the femoral head, tibial spine, and talus. Mechanical lateral distal femoral angle (mLDFA) is the lateral angle formed

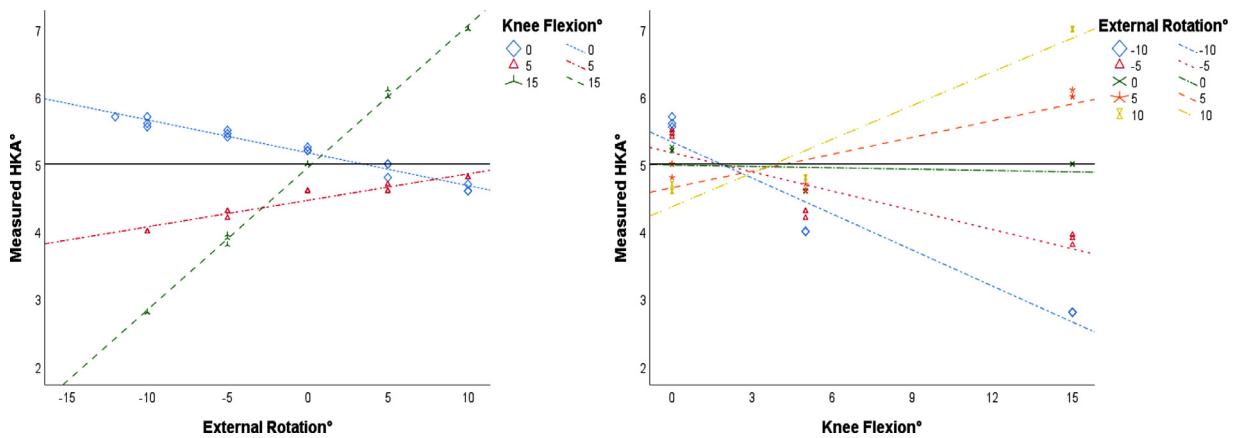


Fig. 4. Scatterplot of the measured HKA (hip knee ankle angle) (on 5° varus model) for knee flexion angles and leg rotation angles. Each measurement was performed using three different X-ray beam heights, which are the different markers on the same leg rotation and knee flexion combinations. Multivariable linear regression analyses of leg rotation and knee-flexion on the measured HKA showed excellent significant correlations ($P < .001$). Leg rotation alone affected the measured HKA significantly ($P < .001$).

between the mechanical axis line of the femur and the knee joint line of the femur in the frontal plane.⁵ This study did not include mechanical medial proximal tibial (mMPTA) angles for analyses. The setup did not allow the tibial sawbone to flex.

The first observer (CN) rated the images twice randomly on independent moments with one week in between, to obtain intra-observer reliability. A second observer (WG) performed HKA measurements on all radiographs to obtain inter-observer reliability.

Statistical analysis

The relationship between the measured HKA/mLDFA and knee flexion and/or leg rotation was determined using multivariable linear regression (SPSS version 25.0, Chicago, IL, USA). The intra-observer reliability was tested for agreement using a two-way mixed Intraclass Correlation (ICC) for absolute agreement. A 2-way random ICC for absolute agreement was used to test the inter-rater agreement.

Results

Intra- & inter-rater reliability

The HKA ICC for intra-observer reliability was perfect 1.000 (95% CI 0.999 - 1.000) and excellent for the mLDFA 0.993 (95% CI 0.986 - 0.996). The HKA inter-rater reliability was nearly perfect with an ICC of 0.999 (95% CI 0.998 - 0.999).

Effects of beam height, knee flexion and leg rotation

Multivariable linear regression analyses of leg rotation and knee-flexion on the measured HKA and mLDFA resulted in excellent significant correlations. Both knee flexion (within the range of 0° and 15°) and leg rotation (within the range of -15° and 10°) were linear related to the measured HKA and mLDFA (Figs. 4 and 5). Knee flexion and leg rotation had a significant interaction ($P < .001$), meaning that the effect of leg rotation is affected by the amount of knee flexion and vice versa. External leg rotation in combination with flexion caused the HKA and mLDFA to be overestimated with greater errors under higher flexion, while a slight flexion equalized the errors induced by rotation (HKA around 3° and mLDFA around 6° of knee flexion). Errors were biggest when there was 10° of leg rotation combined with 15° knee flexion, observed to be high as 2° for the measured HKA and 3° for the measured mLDFA. The HKA measurement error was 1° per 20° of leg rotation without flexion ($P < .01$). When 5° of flexion was added, the HKA measurement error was 0.8° per 20° rotation ($P < .01$). When the leg was in 15° flexion, the HKA measurement error became 4° per 20° rotation ($P < .01$) (Figs. 4 and 5). Leg rotation alone affected both the measured HKA and mLDFA significantly ($P < .001$).

X-ray beam height of 5 cm ($P = .959$) and 10 cm ($P = .967$) above the knee joint did not affect the measured HKA on a significant scale (Fig. 6). Also, X-ray beam height of 5 cm ($P = .775$) and 10 cm ($P = .071$) above the knee joint did not affect the measured mLDFA on a significant scale (Fig. 6).

Discussion

This study showed that leg rotation alone (without knee flexion) can lead to clinically relevant measurement errors when exceeding 9°. When 15° knee flexion was combined with 10° leg rotation the HKA measurement error became 2°, thereby grossly exceeding the

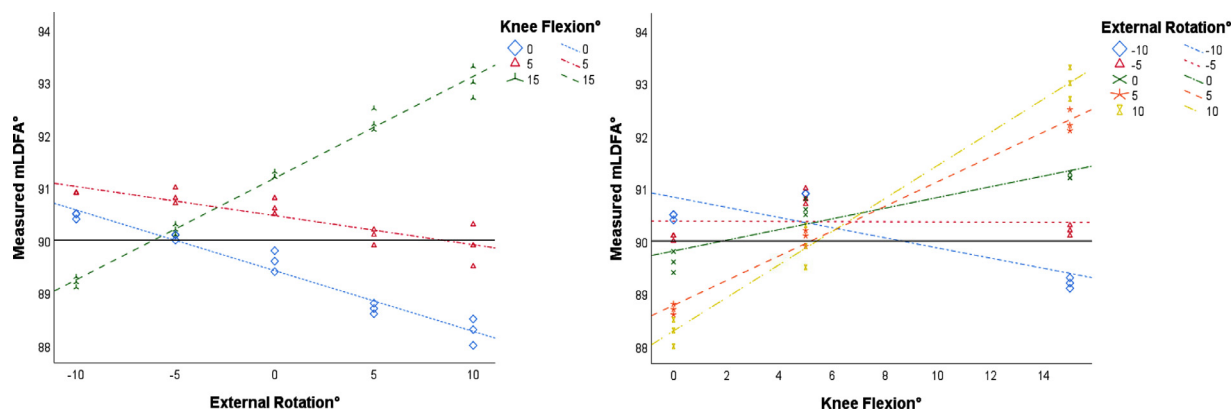


Fig. 5. Scatterplot of the measured mLDFA (mechanical lateral distal femoral angle) (on 90° mLDFA model) for knee flexion angles and leg rotation angles. Each measurement was performed using 3 different X-ray beam heights, which are the different markers on the same leg rotation and knee flexion combinations. Multivariable linear regression analyses of leg rotation and knee-flexion on the measured mLDFA showed excellent significant correlations ($P < .001$). Leg rotation alone affected the measured mLDFA significantly ($P < .001$).

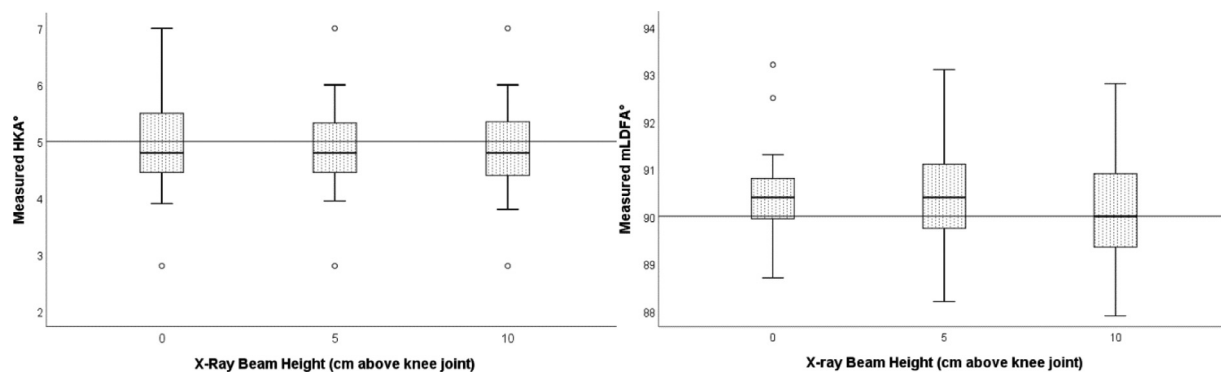


Fig. 6. Boxplot of the effect of different X-ray Beam Heights on the HKA (hip knee ankle angle) and mLDFA (mechanical lateral distal femoral angle) measurements. All measurements were included in the boxplot (with different knee flexion and leg rotation angles). The horizontal black line displays the set 5° varus and 90° mLDFA angle of the model. X-ray beam height of 5 cm ($P = .959$) and 10 cm ($P = .967$) above knee joint did not influence the measured HKA on a significant scale. Also, X-ray beam height of 5 cm ($P = 0.775$) and 10 cm ($P = .071$) above knee joint did not influence the measured mLDFA on a significant scale.

desired osteotomy accuracy of 0.45° of wedge opening.²² Different X-ray beam heights did not affect the measured HKA, regardless of flexion and rotation.

Significant effects of leg rotation on the measured HKA were expected and our results correspond with previously published literature.^{8,10} Radtke et al conducted a study using sawbones and found a similar effect of leg rotation, with 0.0558° measurement error as a result of 1° leg rotation, which is about the same as the 1° measurement error per 20° of leg rotation reported in our study.¹⁰ Brouwer et al conducted a comparative study investigating the relationship between leg rotation, knee flexion and their effects on the measured HKA. Knee flexion was manipulated to a cadaver leg with a transepicondylar rod to control leg rotation.⁸ They concluded that the measured HKA is only significantly affected when leg rotation and knee-flexion are combined.⁸ But our research showed that there are already clinically relevant effects of leg rotation even with full knee extension. Indeed, when knee flexion was combined with leg rotation the HKA measurement error turned out to be huge. The discrepancy in conclusions could be the result of different analyses performed by Brouwer et al and in this study. Brouwer et al only described the HKA in whole degrees while this study aimed to be precise on a 10th of a degree, which means that the desired osteotomy accuracy of 0.45° is achievable.^{8,22}

Both Radtke et al and Brouwer et al did not report the possible effect of different X-ray beam heights on the HKA measurement error.^{8,10} This study investigated the possible effects of using different X-ray beam heights on the measured HKA, with no significant effects. Thus, the study revealed that in clinical care it is not necessary to standardize X-ray beam heights to obtain reliable and reproducible WLRs.

Preoperative planning of lower limb osteotomy surgery requires insight into the mechanical medial proximal tibial angle (mMPTA) and the mechanical lateral distal femoral angle (mLDFA).⁵ This study analysed the behavior of the mLDFA, and the results were comparable to the HKA measurement errors. The greatest mLDFA measurement errors occurred when the knee was flexed in 15° combined with 10° leg rotation, with approximately 3° discrepancy. Unfortunately, due to the hinge setup used in this study only the

femur could tilt backwards in the sagittal plane and therefore mimic knee flexion. The tibia was fixed in the sagittal plane, leading to the exclusion of mMPTA measurements in knee flexion and leg rotation conditions. This study also included measurements performed on a 5° valgus stance. The same effect was observed in terms of the effect of knee flexion, leg rotation, and X-ray beam height on the measured HKA when the model was in 5° varus.

Cooke and Sheehy proposed a WLR protocol with the purpose of eliminating leg rotation, at the same time accounting for torsional deformity of the tibia.¹⁴ They proposed that practitioners align each leg using a rotating platform for each foot. Each platform would be fixed to a certain amount of rotation, determined by flexing the knee and observe the frontal plane while making sure that the flexion plane is in line with the X-ray beam.¹⁴ This protocol is very time-consuming and impractical, while this method heavily relies on the skillset of each practitioner.¹⁸ The Paley and Herzenberg protocol is prone to non-reproducible radiographs, which relies on the skillset of different X-ray technicians to rotate the knee (using the patellae) the same way in clinical care.²⁷ Also, patellar malalignment is quite common in arthritic knees, especially in cases of varus deformities.¹⁷ The Paley and Herzenberg protocol is even more difficult in cases of total knee arthroplasties, with HKA measurement errors up to 3.5°.¹⁸ This was probably caused by postoperative swelling and misleading surgical incisions, while technicians had difficulties to exactly centre the patella. Another important finding of this study is the overall average internal rotation of the lower limbs on WLRs, as the patella is located slightly lateral. Centring the patella as instructed in the Paley and Herzenberg protocol requires an internally rotated lower limb.¹⁸

WLR acquisition guidelines should focus on eliminating leg rotation to minimize the possible effect of knee flexion and account for the mean tibial rotation. It should deliver reproducible radiographs while being quick and easy to perform by X-ray technicians with fixed positioning for the feet and leg rotation. First, there needs to be a consensus about which anatomical landmark is easy to define and useable for knee joint rotation assessments. A viable landmark to define proximal tibial rotation on CT scans is the Akagi line, which can represent the AP alignment of the knee-joint.²⁸ Unfortunately, this line is difficult to locate during physical examination. But the angle between the Akagi line and longitudinal axes of the feet in neutral stance is around 10°.^{24,28-30} Aligning each knee straightforward using anatomical landmarks as the patella, malleoli, or condyles based on the X-ray technicians' experience is very prone to inconsistencies and will result in measurement errors.^{14,17,18}

This report proposes a set of guidelines for reproducible WLR acquisition, based on the findings of this study (control leg rotation and knee flexion, with no effects of different X-ray beam heights) and what is already described in the literature. Patients should be positioned in maximum knee extension, which is more straightforward to apply by X-ray technicians compared to a certain knee flexion angle. The feet are pointed outwards with 10° of rotation and with 10 cm between the centre of their heels. The angle of 10° is situated between the longitudinal axes of the foot.^{24,28-30} Practitioners thereby control the hip rotation, by placing the upper body in a straightforward position.^{7,8,10-13} No handlebars or supports are allowed to ensure full weight-bearing.^{9,32,33} The practitioners additionally instruct the patient to distribute the weight equally over both legs.^{9,35} Each WLR is made bilaterally and remarks about the acquisition should be annotated in the radiograph. These proposed guidelines were yet not tested in a clinical setting.

Aligning the feet at 10° to define the AP alignment does not account for individual variances in tibiofibular torsion and femoral anteversion. However, the standard deviation of tibiofibular torsion and femoral anteversion within the population of both angles is below 9°, which means that approximately 68% of the patients show rotational variances below 9°.^{23,24} Our results show that leg rotation up to ±9° causes a ±0.45° difference in measured HKA, which is an acceptable error in a medial open wedge high tibial osteotomy.^{8,10,22,34} This rule of thumb is also substantiated by the results of Kawahara et al and Jud et al.^{31,34} But with the proposed guidelines we aim at a more reproducible basis for obtaining WLRs. This benefits the postoperative assessment of realized lower limb osteotomies and future studies relying on reproducible WLRs.

In cases with a suspicion of a large lower limb torsional deformity (tibia and/or femur), 3D imaging techniques in the work-up is advisable. Indications for rotational errors on an AP knee radiograph are no (or too much) tibia-fibular overlap and femoral condyle asymmetry.³⁵ When using the proposed protocol with fixed feet, the left and right knee should be presented in the same manner. In cases with differences between left and right, further analyses for possible rotational deformities should be conducted. Also, when there is a suspicion of hyperextension or fixed flexion deformity during physical examination, the WLR becomes unreliable.

Our study has many limitations. First, our model could not represent the knee joint kinematics in terms of soft tissue compression and tension. During knee flexion, knee joint kinematics are complex due to muscle contractions and ligament tensions. Our sawbone model did not incorporate these parameters and the influence of weight-bearing. However, this study tried to mimic the knee-joint articulation by positioning the hinge points of the Ilizarov frame slightly above the knee-joint (on Blumensaat line).³⁶ Every position was checked with a frontal AP for varus alignment and a sagittal radiograph for flexion. Future research should also consider the role of hyperextension in lower limb alignment measurement errors. Second, leg rotation was simulated by rotating the whole sawbone model. In reality, the lower limb has multiple bones and joints which can cause or compensate for leg rotation. Both the ankle and femoral joint can rotate internally/externally. Third, this study did not include the mechanical tibia angle as described by Paley, due to model limitations.⁵ Future studies should investigate the reproducibility of positioning protocols, including the standard measurement protocol proposed by Paley. Fourth, our model did not include the patella, which is important in the WLR protocol of Paley.⁵ The exact influence of patella malalignment on lower limb geometry analyses could be interesting and a topic for future research.

Conclusion

This study showed that leg rotation alone (without knee flexion) can lead to clinically relevant measurement errors when exceeding 9°. When there is 15° of knee flexion and 10° leg rotation the error becomes approximately 2°. Varying X-ray beam heights within a

range of 10 cm does not affect the accuracy. Based on these findings, we propose guidelines for system setup and patient positioning during a WLR that is easy to apply and aims at minimizing errors when measuring the HKA.

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Disclaimer

None

Declaration of competing interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval & informed consent

As the study was performed using sawbones, ethical approval and informed consent was not needed.

Author contributions

WPG and HCN conducted this study, after developing the research question together with RJHC and NvE. KHS helped with the design of the study. WP and HC analysed the data and performed the statistics. HW and RJBS helped with the interpretation of the data. All authors contributed to the writing of the manuscript.

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