The effect of foot rotation on measuring ankle alignment using simulated radiographs: a safe zone for pre-operative planning

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AIM: To assess whether variation in foot rotation, in relation to camera position, affects the reliability of measurement of hindfoot alignment on radiographs and to define a "safe zone" where measurement of the alignment axis and thus preoperative planning is not affected by foot rotation.

MATERIALS AND METHODS: Healthy volunteers were recruited of whom double-sided lower-leg weight-bearing computed tomography (CT) was acquired. Weight-bearing was simulated by means of providing axial compression force equal to the weight of the healthy volunteers. The scans were uploaded into custom-made three-dimensional analysis software to create digitally reconstructed radiographs. For each CT examination, a coordinate system was determined, which defines the neutral position of the leg. Rotation about the *z*-axis of this coordinate system simulates endo- and exorotation of the foot. Subsequently, radiographs were reconstructed for the leg between 30° of endorotation and 45° of exorotation, and the relation between the observed alignment axis and foot rotation was determined.

RESULTS: A total of 20 healthy volunteers were included, 10 males (mean age 37.7±11.1) and 10 females (mean age 34±10.3). Per 5° of leg rotation, the alignment axis translated with a mean of 6.86% (SD ±13.1). No significant difference in position of the alignment axis was seen between 10° of endorotation and 10° of exorotation compared to the neutral ankle position.

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CONCLUSION: The "safe zone" for imaging the hindfoot alignment axis, is between 10° endo- and 10° exorotation of the foot.

Introduction

Adequate preoperative planning is essential to ensure successful treatment outcome in ankle realignment surgery.[1–3] Additionally, adequate correction of bone geometry positively affects ankle joint kinematics, articular congruency, and loading distribution.[4,5] Moreover, when one reaches adequate bone geometry correction, the risk of osteoarthritis is decreased, and symptoms of pain are alleviated thereby improving physical functioning.[6,7] For these reasons, prior to performing realignment procedures, correct measurement of the malalignment and definition of the degree to which correction surgery is needed, are essential. In clinical practice, these radiographs are often not created with the central X-ray parallel to the ankle joint, despite this requirement during validation of these measurements.[8–16] Reasons for this may be either logistically related or patient related.

Although measured using two-dimensional (2D) radiographic images, ankle alignment actually concerns a three-dimensional (3D) phenomenon.[15,17,18] Variation in foot rotation is likely to affect the image projection and may therefore affect the reliability of the alignment measurement and the subsequent preoperative planning, in turn potentially leading to suboptimal postoperative results[15,17,18]; however, the current literature does not describe a safe zone regarding endo- and exorotation of the foot and measuring ankle alignment using 2D radiographs.

To ensure adequate preoperative planning and optimise results of ankle realignment surgery the effect of foot rotation on measuring ankle alignment needs to be assessed. For this techniques have already become available such as digitally reconstructed radiographs (DRRs) that can be generated from different views, to simulate leg rotation without the need of acquiring multiple radiographs, and exposing participants to additional radiation load.[19] Therefore, the objective of the present study was to investigate the influence of foot rotation on ankle alignment measurement and to define the "save zone" for which the ankle alignment measurement shows no significant difference compared to the neutral foot position.

Materials and methods

Study population

For this study volunteers were recruited through public flyers distributed in University of Amsterdam hospital. It was decided to include an equal number of males and females, in order to prevent any bias concerning gender and its relation to potential differences in alignment.[20,21] Volunteers were included who (1) were healthy, (2) had not suffered a previous trauma or condition of the lower leg that required medical attention, and (3) were at least 16 years old. Volunteers were excluded if they (1) had undergone a computed tomography (CT) in the previous year, (2) or were planned to undergo a CT in the upcoming year, in order to minimise their radiation load. Women who (3) were pregnant or wanting to become pregnant were excluded from the study cohort. Finally, (4) volunteers who were had current lower extremity complaints were also excluded.

Ethical approval

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments (reference: 2017_039#B2017175a, approval date 24 March 2017). Informed consent was obtained from all individual participants included in the study.

Image acquisition

For measurement of the ankle alignment, use of the mechanical leg axis (MLA) was chosen, which normally runs from the femoral head to the lowest point of the calcaneus.[13] In order to minimise radiation load and to avoid a high number of radiographs to assess different projection angles, DRRs were created. This required acquiring a bilateral CT of the knees, tibiae, and ankles in a loaded condition (Philips Brilliance 64 CT system, voxel size $0.46\times0.46\times0.45$ mm^3, 120 kV, and 160 mAs).

Weight-bearing imaging was simulated by means of a custom-build device providing axial compression force onto the plantar foot sole (Fig 1). To ensure adequate loading of the ankle joint, the weight of each volunteer was measured using a scale prior to acquiring the CT examination. Each participant was requested to be seated on the device in a horizontal sitting position with extended legs. Subsequently, each volunteer was requested to place their feet on the moveable footplate and provide counter force to the axial compression force by active extension of both legs, which should thereby match their bodyweight. By means of a digital force meter, which was attached to the fixated frame, the force exerted by each volunteer was measured and adjusted until the volunteers' weight matched the exerted force. Subsequently the CT examination was undertaken.
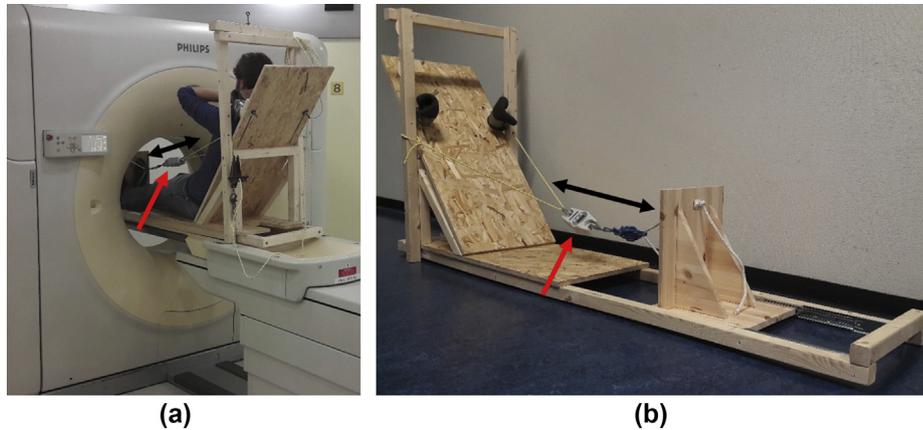
Figure 1 Simulated weight-bearing CT examinations using a custom-built device (a) with a movable platform allowing axial compression force on the lower legs (b, black arrow) and for which the pulled weight was measured using a Newton meter (b, red arrow).

Image analysis

As the CT examination only included the lower leg (excluding the femur), the MLA was drawn from the tibia plateau to the lowest point of the calcaneus (adjusted MLA: aMLA; see Fig 2). Additionally, for alignment measurement
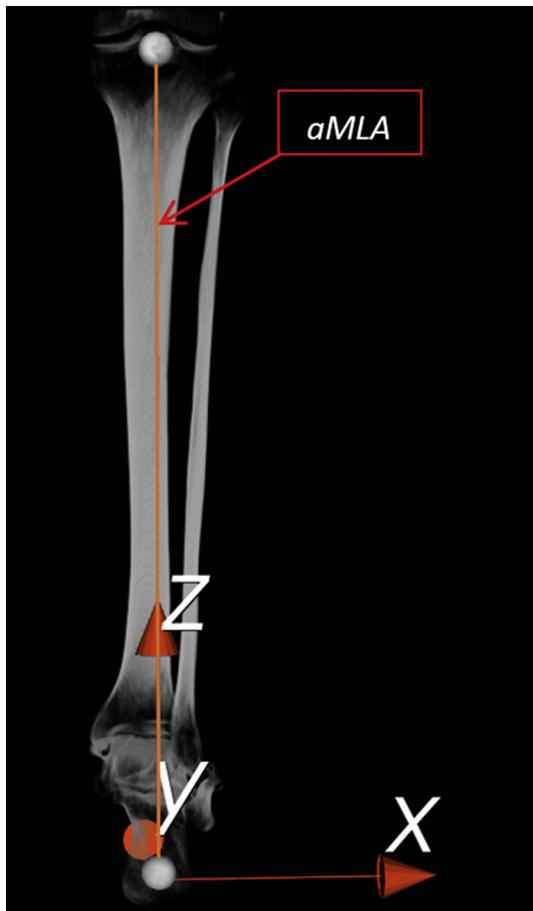

Figure 2 Placement of the coordinate system (orange) and the MLA (white line) through the lowest point of the calcaneus and centre of the tibia plateau.

in each scan, the aMLA intersection point (aMLAIP) at the level of the tibiotalar joint line was defined (Fig 3).

To determine the effect of the foot rotation on assessment of the ankle alignment, 20 double-sided lower-leg weight-bearing CT examinations were evaluated using a custom-made 3D analysis program.[19] All left legs were mirrored to match the right leg to keep analysing left and right legs equivalently. In the 3D image data, an orthogonal coordinate system was manually drawn with the longitudinal axis (z) from the middle of the tibia plateau to the lowest point of the calcaneus (aMLA), the sagittal axis (y) perpendicular to the z-axis through the centre of the second metatarsal. The frontal x-axis was positioned perpendicular to the z- and y-axes (Fig 2). After placing the coordinate system, the DRRs were created through volume rendering of the acquired CT examinations. The ankle was considered in the neutral position if the imaging plane was perpendicular to the y-axis and the z-axis was pointing in an upward direction.

Simulation experiments

To investigate the effect of the DRR projection angle, thus the amount of endo- or exorotation of the foot, on the translation of the aMLAIP, the CT image was virtually rotated around the z-axis of the local coordinate system between 30° endorotation and 45° exorotation, in steps of 5° each (Fig 4). A DRR was generated for each projection angle and the translation of the aMLAIP was measured using ImageJ (U. S. National Institutes of Health, Bethesda, MD, USA).[22] Per 5° of rotation the relative translation of the aMLAIP was recorded. The relative translation of the aMLAIP was expressed as the percentage translation in relation to the total tibiotalar joint width. The difference in aMLAIP in relation to the measurement in neutral position was reported using the mean difference (MD), standard deviation (SD) and whether this difference was significant (Fig 3).

The window of rotation that represented the optimal projection angle (e.g., "safe zone") was defined as the range for which rotation of the foot did not significantly affect the
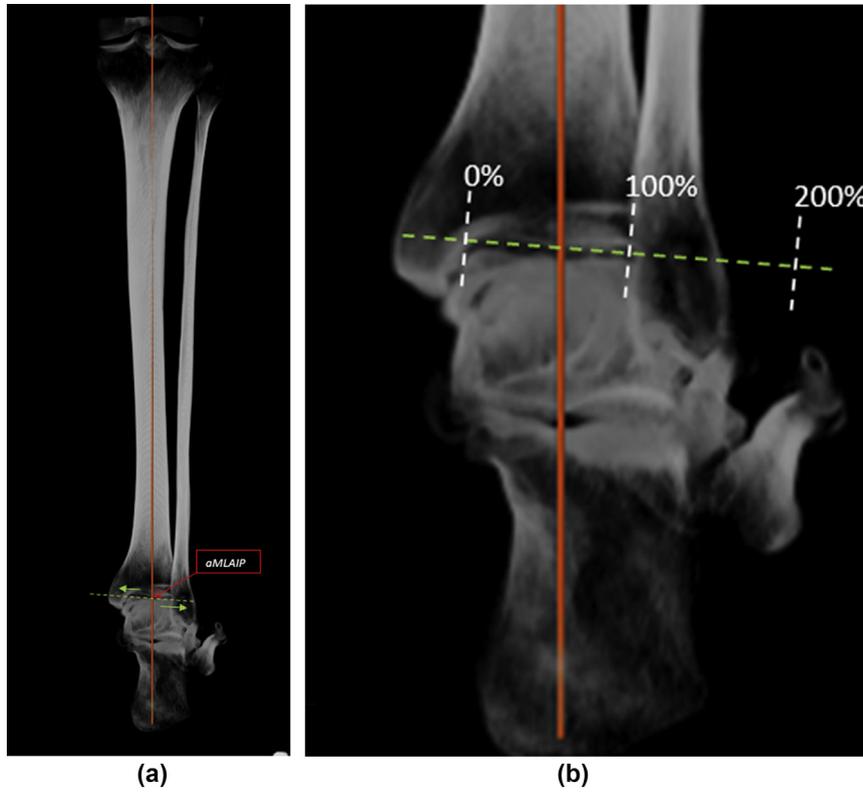
(a)   **(b)**

Figure 3 Adjusted mechanical leg axis (aMLA; orange line); tibiotalar joint line (dashed green line). (a) Translation of the aMLA intersection point (aMLAIP) over the tibiotalar joint line as described when comparing pre- and postoperatively after realignment surgery (green arrows). (b) The relative translation of the aMLAIP over the tibiotalar joint line scored from 0% (fully medial) and 100% (fully lateral), or even further (>100%).
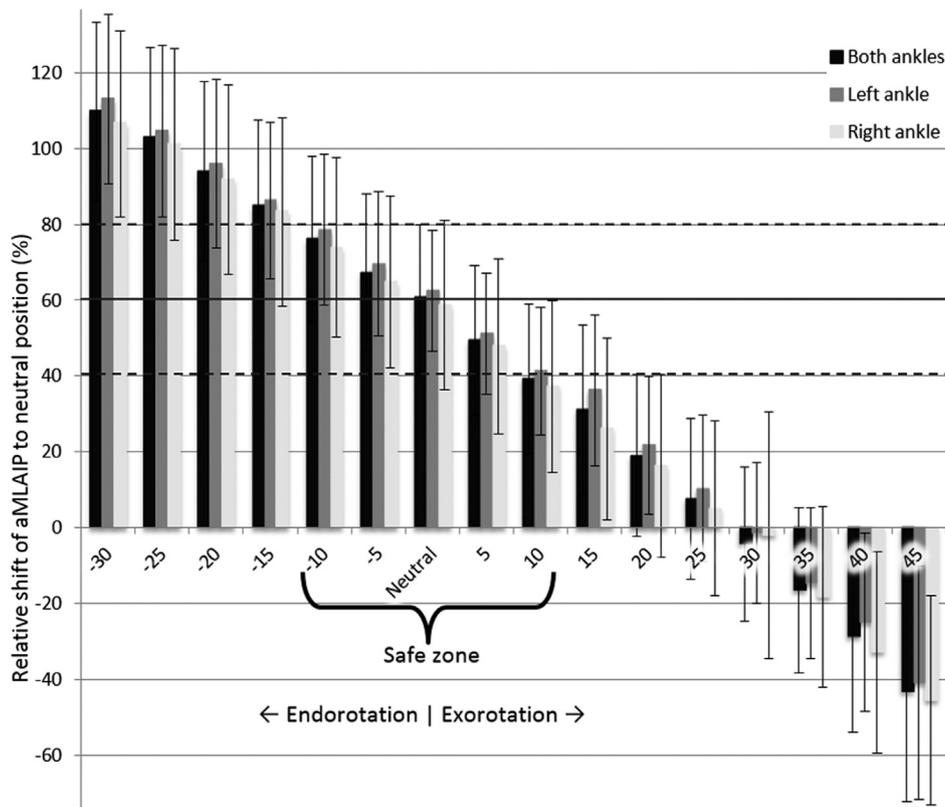

Figure 4 The aMLAIP as a function of the projection angle forming a part of a sinusoidal curve. The whiskers represent the standard deviation. The solid and the dashed lines represent the mean aMLAIP and the ±1 SD, respectively. The "safe zone" includes the range for which the projection angle did not lead to significant differences in measurement of the aMLAIP.

relative translation of the aMLAIP compared to the neutral position of the DRR.

To evaluate the effect of placement of the coordinate system on the outcome measurement, the inter- and intra-observer reliability was assessed. Two orthopaedic researchers (G.V., J.D.) therefore individually and independently performed the placements of the coordinate systems.

Statistical analysis

Normally distributed data were expressed with a mean and SD or 95% confidence interval (95% CI). Skewed data were expressed with a median and range. The effect of rotation of the foot on the aMLAIP and the optimal projection angle was assessed using an ANOVA for repeated measurements with a post-hoc Bonferroni correction.

Inter- and intra-observer reliability was assessed using the intraclass correlation coefficient (ICC). The ICC was interpreted as poor ($\leq$0.40); moderate (0.40–0.75); substantial (0.75–0.90); and excellent reliability (>0.90).[23]

A *p*-value of <0.05 was considered statistically significant. For the statistical analysis SPSS Statistics version 24.0 was used (IBM SPSS Statistics for Windows, version 24.0. IBM, Armonk, NY, USA).

Results

A total of 10 healthy men (mean age 37.7±11.1) and 10 healthy women (mean age 34±10.3) were included. The included volunteers matched their weight on the simulated weight-bearing CT with a mean error of −1.8kg (SD±6.4). The overall mean aMLAIP with the DRR in neutral position was 60.62% (SD±19.34; Fig 4). The aMLAIP of the left foot (mean 62.54%; SD±15.92) and the right foot (mean 58.7%; SD±22.40) were significantly different (*p*<0.005). In male participants (63.97%; SD±17.69), the mean aMLAIP was

9.35% (*p*=0.019) more lateral compared to female participants (54.62%; SD±17.11).

Projection angle

Per 5° of rotation of the foot the aMLAIP translated with a mean of 6.86% (SD±13.1) over the tibiotalar joint line. Compared to the neutral position endo- and exorotation of the left ankle did not affect the position of the aMLAIP between 10° of endorotation and 10° exorotation in males. In female participants the aMLAIP was not affected between 20° of endorotation and 15° of exorotation. For the right ankle no significant effect was seen between 20° of endorotation for both male and female participants and 15° of exorotation for male participants and 20° of exorotation for female participants (Table 1). When pooling both the left and right ankle the "safe zone" 10° of endorotation to 10° of exorotation in male participants and 15° of endorotation to 10° of exorotation in females (Fig 5).

Reliability analysis

Placement of the coordinate system and 3D aMLA for subsequent alignment measurement in a 2D DRR simulation had excellent intra-observer reliability (ICC 0.937; 95% confidence interval [CI]: 0.922–0.950) and substantial interobserver reliability (ICC 0.812; 95% CI: 0.672–0.896).

Discussion

This study was performed to assess the effect of foot rotation on the measurement of ankle alignment using 2D radiographs, and to indicate whether this may bias for example preoperative planning. The most important finding of the present study is that that the projection angle, i.e., the position of the foot, influences the measurement of the aMLAIP on an anteroposterior projection of the lower leg; however, it was found that there is a

Table 1
Effect of the projection angle on the MLAIP, mean difference (MD) compared to the neutral position.

	Left ankle Mean difference,% (*p*-value)		Right ankle Mean difference,% (*p*-value)		Both sides Mean difference,% (*p*-value)	
	Male	Female	Male	Female	Male	Female
30° endorotation	−54.72 (*p*<0.005)	−49.10 (*p*<0.005)	−52.37 (*p*=0.001)	−52.60 (*p*<0.005)	−53.54 (*p*<0.005)	−45.67 (*p*<0.005)
25° endorotation	−45.55 (*p*<0.005)	−41.63 (*p*=0.009)	−48.41 (*p*=0.003)	−46.26 (*p*=0.005)	−46.98 (*p*<0.005)	−38.76 (*p*<0.005)
20° endorotation	−37.18 (*p*<0.005)	−31.61 (NS)	−38.13 (NS)	−38.10 (NS)	−37.66 (*p*<0.005)	−29.68 (*p*=0.007)
15° endorotation	−27.95 (*p*=0.023)	−22.58 (NS)	−29.43 (NS)	−28.08 (NS)	−28.69 (*p*<0.005)	−20.15 (NS)
10° endorotation	−19.49 (NS)	−14.92 (NS)	−19.48 (NS)	−19.19 (NS)	−19.49 (NS)	−11.88 (NS)
5° endorotation	−9.02 (NS)	−5.99 (NS)	−9.99 (NS)	−11.11 (NS)	−9.51 (NS)	−3.37 (NS)
Neutral						
5° exorotation	11.56 (NS)	11.97 (NS)	6.94 (NS)	6.38 (NS)	9.25 (NS)	14.36 (NS)
10° exorotation	21.34 (NS)	21.61 (NS)	19.12 (NS)	16.68 (NS)	20.23 (NS)	24.32 (NS)
15° exorotation	28.76 (*p*=0.015)	31.74 (NS)	32.34 (NS)	25.73 (NS)	30.55 (*p*<0.005)	33.91 (*p*<0.005)
20° exorotation	40.67 (*p*<0.005)	40.13 (*p*=0.015)	43.73 (*p*=0.017)	35.02 (NS)	42.20 (*p*<0.005)	42.76 (*p*<0.005)
25° exorotation	51.38 (*p*<0.005)	53.19 (*p*<0.005)	57.89 (*p*<0.005)	45.10 (*p*=0.008)	54.64 (*p*<0.005)	54.76 (*p*<0.005)
30° exorotation	64.27 (*p*<0.005)	64.43 (*p*<0.005)	67.22 (*p*<0.005)	58.47 (*p*<0.005)	65.74 (*p*<0.005)	66.63 (*p*<0.005)
35° exorotation	80.59 (*p*<0.005)	75.78 (*p*<0.005)	78.64 (*p*<0.005)	65.23 (*p*<0.005)	79.62 (*p*<0.005)	75.69 (*p*<0.005)
40° exorotation	88.14 (*p*<0.005)	87.32 (*p*<0.005)	95.20 (*p*<0.005)	75.11 (*p*<0.005)	91.67 (*p*<0.005)	86.39 (*p*<0.005)
45° exorotation	105.68 (*p*<0.005)	105.83 (*p*<0.005)	108.75 (*p*<0.005)	88.77 (*p*<0.005)	107.22 (*p*<0.005)	102.48 (*p*<0.005)

NS, not significant.
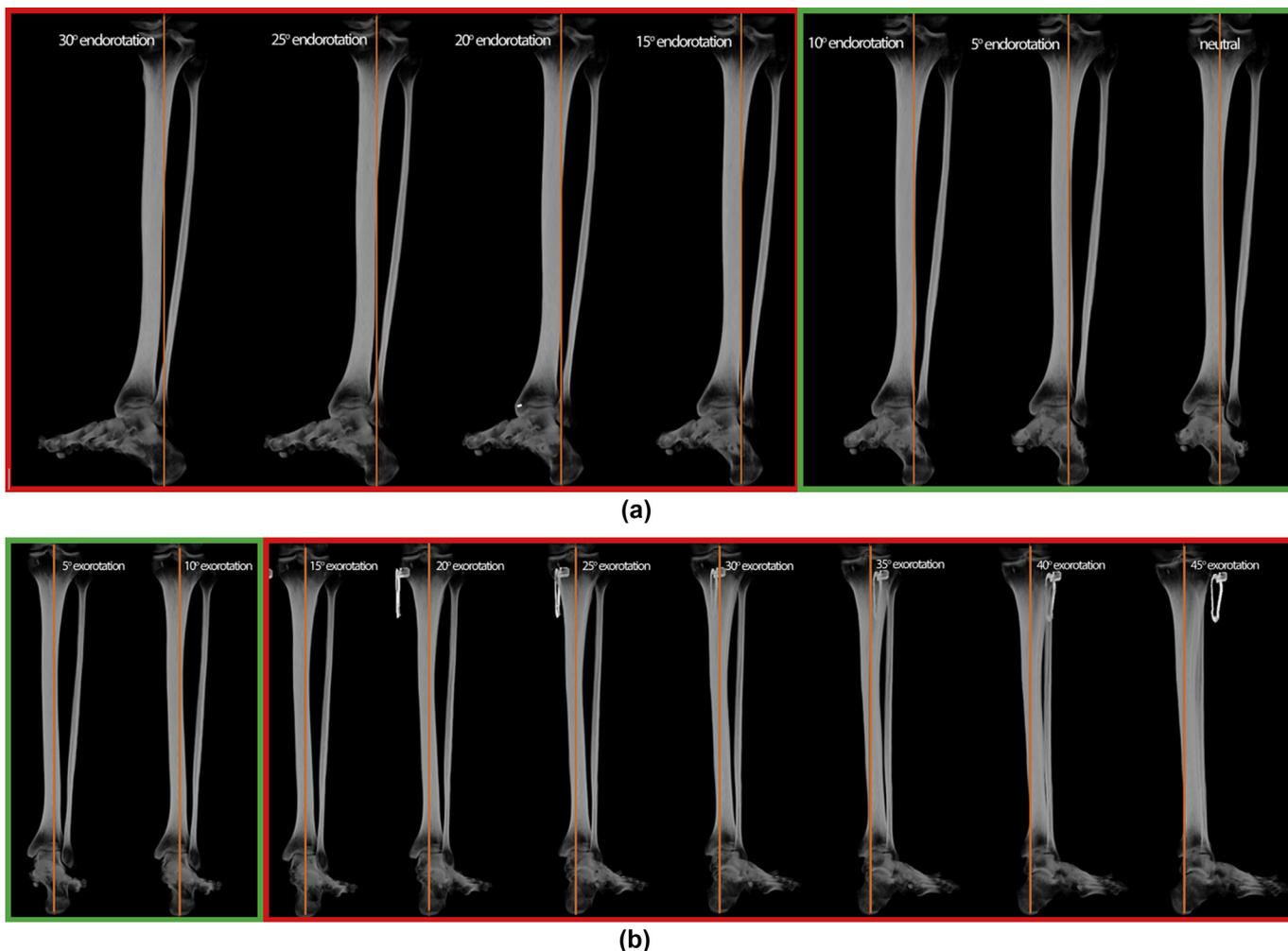
(a)

(b)

Figure 5 Rotation of the DRR around the longitudinal (*z*-)axis showing the translation of the aMLAIP (orange line). Green box: no significant change compared to the aMLAIP in neutral position. Red box: significant change compared to the aMLAIP in neutral position.

specific "safe zone" between 10° of endo- and exorotation of the foot in males and 15° of endorotation and 10° of exorotation in women. Within this range of foot rotation the aMLAIP is not significantly different compared to its value in the neutral position.

A previous study has shown that the assessment of ankle alignment on an anteroposterior radiograph is sensitive to changes when the foot rotated ≥5° significantly affecting outcome measurements.[15] One reason for the reduction in reliability in the measurement of ankle alignment is that axial rotation impairs the visibility of important landmarks, such as the lowest point of the calcaneus, the centre of the tibia shaft as well as the projection of the foot.[15] The present study showed a lower sensitivity to alterations of the projection angle when measuring ankle alignment when using the aMLAIP. This lower sensitivity may be due to a simulation based on 3D imaging instead of 2D, increasing the reliability of the variating projection angle. Even though it may be inferred that 3D methods may be preferable for surgical planning, they are associated with higher costs, higher radiation load and longer waiting lists. The present results showed that, as long as foot rotation stays within the

range of 10° of exo- and endorotation, 2D radiographic measurements were not affected.

Furthermore, the present study included a 3D rotational simulation for a 2D alignment measurement of which the aMLA lies slightly posteriorly from the tibiotalar joint line. Rotation around the longitudinal axis will therefore eventually visualise the oblique course of the aMLA and from that point of rotation (outside of the "safe zone") lead to significant measurement differences of the aMLAIP. Ranges outside of this "safe zone" would therefore be visualised as a steep positive and negative curve, which was found when rotation exceeded 10° of endo- and exorotation (Fig 4). Further progression to endo- and exorotation lead to a shift of the aMLAIP to the outer medial and lateral edges of the tibiotalar joint line, represented by the slope coefficient nearing 0 (the more horizontal area of a sinusoidal curve).

Measurement of the MLAIP was initially designed to be measured on a long-leg radiograph, whereas this study only visualised the lower leg and used the aMLA from the centre of the tibia plateau to the lowest point of the calcaneus. Use of the lower leg, instead of long-leg CT examination, lead to a lower radiation load without hampering results as, even in

case of malalignment, the MLA crosses the knee joint between the medial and lateral edges of the tibia plateau.[13,18] Published studies suggest that when the aMLA passes through the centre of the tibia plateau, it is more similar to the real-life situation.[13,18] To mimic the real live situation to a further extent, weight-bearing CT examinations were made thereby minimising the effect of the talar tilt on alignment measurement.[24] To which degree rotation of the foot found for the aMLAIP affects measurement of the MLAIP on a long-leg view is unsure, but the negative effect of foot rotation on the reliability of the alignment measurement is an established fact.[15,17,18]

This study is limited in its design as weight-bearing CT examinations were simulated because there was no device available in our institution offering the possibility to create full weight-bearing CT examinations. Placement of the coordinate system and measurement of the aMLAIP proved reliable; however, the measured aMLAIP position may have been affected by inter-subject variation and position of the second metatarsal, which was essential to definition of the neutral position. Strengths of this study are that this study includes a unique dataset of simulated weight-bearing CT examinations of a healthy (male and female) population without cavus or valgus foot deviations (according to Meary's angle). Additional strengths are that the study minimises any potential effect of induced bias of unequal gender distribution, dominant leg, pathological bone morphology or unloaded joints (e.g., talar tilt) on the present study results).

Based on the chosen location of the aMLA the results of this study may also be applicable on full-leg radiographs[13,18]; however, this first requires a solid definition of the exact location of the MLA at the level of the tibia plateau and the associated clinical implications assessed through radiographic and procedural standardisation.

In conclusion, based on DRRs for different rotational positions of the foot it was shown that ankle alignment measurement is significantly affected if foot rotation exceeds 10° of endo- or exorotation. To optimise preoperative planning and subsequently postoperative results the foot should be placed in neutral position parallel to the central X-ray of the system with a maximal foot rotation of 10°.

Conflict of interest

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