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Joint-line obliquity angle is significantly affected by hip abduction and adduction: A simulated analysis

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Abstract

Purpose
Different methods for quantifying joint-line obliquity (JLO) have been described, including joint-line obliquity angle (JLOA), Mikulicz joint-line angle (MJLA) and medial proximal tibial angle (MPTA). The goal of the present study was to quantify the variation of JLOA based on the position of the hip. The hypothesis of our study is that JLO is significantly influenced by the abduction/adduction of the limb, unlike MJLA.

Methods
One hundred long-leg-weightbearing X-rays were used. At time 0 and after 30 days, two observers performed different measurements, including (1) distance between pubic symphysis and center of the femoral head, (2) distance between center of the femoral head and center of the ankle joint, (3) distance between center of the ankle and medial malleolus, (4) hip-knee-ankle angle, (5) MPTA, (6) lateral distal femoral angle, (7) joint-line congruency angle, (8) JLOA, (9) MJL and (10) angle between Mikulicz line and line perpendicular to the ground. The changes of the JLOA based on the position of the hip (abducted, neutral, bipedal stance adduction and monopodal stance adduction) were calculated with trigonometric formulas and with simulation on an orthopaedic planning digital software.

Results
The JLOA change between adducted and abducted positions was on average 12.8° (SD 0.9 mm). The MJL did not vary significantly based on hip position.

Conclusions
The adduction/abduction of the lower limb has a considerable impact on JLOA. Methods like MJLA which are not affected by hip position should be preferred for JLO evaluation.

Level of Evidence
Level III, diagnostic study.

Keywords: femoro-tibial morphology, hip position, knee alignment, knee joint-line obliquity (JLO), preoperative measurement.

Abbreviations: BIP-ADD, hip adduction as in a weightbearing bipedal stance position; HKA, hip-knee-ankle angle; HTO, high tibial osteotomy; JLCA, joint-line congruency angle; JLO, joint-line obliquity; JLOA, joint-line obliquity angle; LDFA, lateral distal femoral angle; MAX-ABD, hip abducted of the same angle calculated for the maximum adduction position; MAX-ADD, maximally adducted hip, as in a monopodal stance; MJLA, Mikulicz joint-line angle; MPTA, medial proximal tibial angle; NEUT, neutral position of the hip; OWHTO, opening wedge high tibial osteotomy; TKR, total knee replacement.

INTRODUCTION

Knee joint-line obliquity (JLO) is the inclination of the joint line on the coronal plane with respect to the horizontal plane or the mechanical axis of the lower limb [3]. JLO evaluation has become crucial in different surgical procedures around the knee, including osteotomies and knee replacements.
Pre- and postoperative JLO is usually evaluated during osteotomy planning, with the goal of avoiding excessive change of the JLO after realignment. Several recent studies focused on defining maximum acceptable JLO values after osteotomy [2, 27], identified the risk factors for excessive postoperative JLO [31], and studied the role of ankle, subtalar, and hip joints in affecting or mitigating postoperative JLO modifications [15, 18, 33]. JLO evaluation is also crucial in total knee replacement (TKR). The adoption of techniques such as kinematic and functional alignment has also brought greater attention to the analysis and preservation of the joint-line inclination [12, 22, 35].
In addition, several recent studies [13, 23] have introduced classification systems in the coronal plane that differentiates various phenotypes based on bony landmarks and measurements such as hip-knee-ankle (HKA) angle and JLO.
Different methods of measuring JLO can be found in the literature [5, 16, 37]. Three methods are commonly used to quantify JLO: (1) the knee JLO angle (JLOA, angle between the line tangent to the tibial condyles and a line parallel to the ground); (2) the Mikulicz joint-line angle (MJLA) (the angle between the bisector of the joint-line congruency angle (JLCA) and the line from the center of the femoral head to the center of the ankle joint, also known as Mikulicz line or weightbearing line) and (3) Medial proximal tibial angle (MPTA, angle between the line tangent to the posterior tibial condyles and the mechanical axis of the tibia measured on the medial side).
These methods for JLO measurement (JLOA, MJL and MPTA) are not without limitations and no gold standard has been identified.
Although JLOA, to date, is the most widely used method, this angle is affected by the position of the lower limb (hip adduction or abduction in the coronal plane) during long leg weightbearing X-rays acquisition. On the other hand, the MJLA and MPTA are independent of the lower limb position. As a main limitation of the MPTA for measuring JLO, this angle does not take into account the mechanical axis of the entire lower limb, but of the tibia only.
The main goal of the present study was to quantify the variation of the JLOA based on hip abduction-adduction. The second aim of the study was to compare JLOA and MJL angles in terms of intra- and interobserver reliability. The hypothesis of our study is that JLO is significantly influenced by the abduction/adduction of the limb, unlike MJLA.

METHODS

This study was approved by the local ethical committee (University of Turin; protocol #01032021).
Between January 2018 and December 2020, a total of 165 consecutive (328 knees) long-leg-weightbearing X-rays were obtained at our institution and were retrospectively evaluated. Long-leg-weightbearing X-rays acquisition protocol was: bipedal stance with patella facing forward, both knees in full extension and the X-ray central beam targeted between the knees and perpendicular to the cassette at a distance of 1.5 m from the tube.
All examinations included in the study were performed as part of clinical or preoperative radiological evaluation of patients affected by lateral or medial knee pain who were active, with no signs of instability and with clinical varus or valgus malalignment to assess coronal alignment (varus and valgus), degree and level of deformity, as well as stage of osteoarthritis.
To minimise measurement errors, exclusion criteria were as follows: (1) previous surgeries on the femur or tibia of the examined limb, (2) previous fractures, (3) congenital or acquired malformations, (4) rheumatoid arthritis, (5) flexion contracture, (6) hip, knee or ankle joint replacement, (7) torsional deformities, (8) Kellgren–Lawrence >2 stage of arthritis, (9) age >65 years old and (10) incorrect acquisition of the images.

Radiographical evaluation and measurements were performed at time 0 and time 1 (after 30 days) by two sports medicine fellowship-trained orthopaedic surgeons (F. R and D. E. B).
Alignment evaluation
RadiAnt DICOM Viewer (Medixant) was used to perform deformity evaluation of the examined limbs. The least count of the software was 0.1° for angles and 0.1 mm for distances.
Deformity evaluation measurements included: (1) hip-knee-ankle angle (HKA, angle between a line from the center of the femoral head to the center of the knee and the line from the center of the knee to the center of the ankle); (2) the angle between the Mikulicz line (also known as weightbearing line) and a line perpendicular to the ground (to determine the adduction angle during X-ray acquisition); (3) lateral distal femoral angle (LDFA, angle between a line tangent to femoral condyles and the mechanical axis of the femur measured on the lateral side); (4) JLCA (angle between a line tangent to distal femoral condyles and a line tangent to the proximal tibial condyles) and (5) MPTA (angle between a line tangent to tibial plateau and the mechanical axis of the tibia measured on the medial side) (Figure 1).
The knee JLO was also evaluated with different methods, including (1) joint-line obliquity angle (JLOA) (angle between a line tangent to the proximal tibial plateau and the horizontal line of the ground) with a positive value (+) indicating a medial opening angle and a negative value (−) a lateral opening angle; (2) MJLA, angle between the bisector of the JLCA and the Mikulicz line measured on the medial tibial side) and (3) MPTA. The main JLO measurements are schematically described in Figure 2.

Trigonometric formulas
Four different positions of the lower limb were considered: (1) center of the ankle joint under the center of the femoral head (neutral position, NEUT); (2) legs together with right and left medial malleoli touching each other (hip adduction as in a weightbearing bipedal stance position, BIP-ADD); (3) center of the ankle under the pubic symphysis (maximally adducted hip, as in a monopodal stance, MAX-ADD); (4) the hip abducted of the same angle calculated for the maximum adduction position (MAX-ABD) (Figure 3). To obtain JLO variation based on the position of the hip with trigonometric formulas, the following linear measurements were calculated with RadiAnt DICOM Viewer (Medixant): (1) distance between the pubic symphysis and the center of the femoral head (distance a), (2) the distance between the center of the femoral head and the center of the ankle joint (distance b), (3) the distance between the center of the ankle and the medial malleolus (distance c) (Figure 4a). The formulas used to simulate BIP-ADD and MAX-ADD were obtained following basic trigonometric rules. The angle α was defined as the maximum adduction angle, as in a perfect monopodal stance (MAX-ADD position), and was obtained with the formula $\alpha = \arcsin(a/b)$. The angle β was defined as bipedal adduction angle (BIP-ADD position) and was obtained with the formula $\beta = \arcsin[(a–c)/b]$ (Figure 4b,c).
To obtain the total possible variation of the JLOA from the MAX-ADD position to the MAX-ABD position, the maximum adduction angle was multiplied by 2 (Figure 4d).
Considering that in the neutral position the weightbearing line and the floor line are perpendicular and closely related, any variation in the obliquity of one can be transposed onto the other, based on trigonometrical principles. Consequently, it was assumed that angles α and β do not only represent the degree of lower limb adduction but also the variation of the JLOA with respect to the limb in neutral (NEU) position (Figure 5).

Simulation of knee JLO variation with digital software
In addition, the changes of the knee JLO were calculated based on the position of the hip with a simulation performed on TraumaCad® TM 2.4 digital software (Brainlab). The least count of TraumaCad® was 1° for angles and 1 mm for distances. All images were imported into the software and were calibrated using a 100 × 100 mm reference square. To simulate different positions of the lower limb, both legs were isolated using the segmentation function and rotated on the center of

rotation of the hip (Figure 6). The four different lower limb adduction/abduction positions were as described above: NEUT, BIP-ADD, MAX-ADD and MAX-ABD (Figure 6). The MJL angle and the JLO angle were also manually measured with TraumaCad® software using the same method described above (Figure 7).

Statistical analysis

Data were reported as mean and standard deviation (SD). All radiographic measurements (at time 0 and time 1) on DICOM viewer were compared for each rater to assess intra and interobserver repeatability. The normality of the distribution of the measurements was tested with the D'Agostino–Pearson test. The intraobserver reliability was tested with the Pearson correlation index (*r*) in case of normal distribution or the Spearman's rank correlation coefficient (rho) in case of not normal distribution. The interobserver reliability was calculated with intraclass-correlation-coefficient (ICC) and Kappa coefficient. Reliability ICC values below 0.5 were considered poor, between 0.5 and 0.74 moderate, between 0.75 and 0.9 reasonable, and above 0.9 excellent reliability. A 95% confidence interval (CI) of the estimated ICC was used. Kappa reliability values were interpreted as follows: ≤0 no agreement, 0.01–0.20 none to slight agreement, 0.21–0.40 fair agreement, 0.41–0.60 moderate agreement, 0.61–0.80 substantial agreement and 0.81–1.00 almost perfect agreement. A 95% CI of the estimated Kappa coefficient was used.
The measurements obtained with trigonometric formulas were compared with the measurements obtained with TraumaCad® software using the Pearson's correlation coefficient (after testing for normal distribution).
Statistics was performed with MedCalc Statistical Software Version 16.4.3 (MedCalc Software).
A change of 4° of JLO with a standard deviation around 3–5° was considered as clinically relevant. A priori sample size calculation was performed with a statistical power greater than 80% and a statistical significance of 5% ($\alpha = 0.05$, $\beta = 0.2$), resulting in a minimum number of patients needed of 40. A sample size of 100 knees was therefore deemed appropriate considering also that the minimum number of samples required for reliability studies is 42 (sample size calculation with $\alpha = 0.05$, $\beta = 0.2$, p [0] = 0.6, p [10] = 0.85) [9].

RESULTS

Of 165 patients, only 100 knees (100 patients) met the inclusion criteria and were enrolled in the present study. The mean age of the patients was 57.6 ± 5.3 year. Of the total, 57 patients (57%) were male. To simplify the measurements for the two raters, only right knees were studied.
Figure 8 shows the inclusion process according to the STROBE (strengthening the reporting of observational studies in epidemiology) criteria. Patient demographic data and radiographical measurements are summarized in Table 1. Intra- and interobserver reliability were high for all measurements (Table 2).
Long-leg X-rays were obtained with the hip adducted in 75% (average 1.8°, range 0.1–4.3°) of cases and abducted in 25% (average −0.9°, range from −0.1 to −4°) of the patients.
The JLOA was significantly affected by the position of the hip. The JLOA difference between neutral adduction of the hip (NEU) and maximum adduction of the hip (MAX-ADD) was 6.4 ± 0.5° on average (with the formulas obtained from RadiAnt) and 6 ± 1° (on TraumaCad® simulation). The JLOA difference between neutral adduction of the hip (NEU) and bipedal stance adduction of the hip (BIP-ADD) was 4.6 ± 0.4° on average (with the formulas obtained from RadiAnt) and 5° ± 1° (on TraumaCad® simulation). The JLOA difference between MAX-ABD and MAX-ADD was 12.8 ± 0.9° on average (with the formulas obtained from RadiAnt) and 12 ± 2° (on TraumaCad® simulation).
A high correlation was found between the MJLA measured with RadiAnt and the MJLA measured with TraumaCad® ($r = 0.9$, $p < 0.0001$) as well as the JLOA measured with RadiAnt and the JLOA measured with TraumaCad® ($r = 0.97$, $p < 0.0001$). A high correlation was found between the α angle obtained with trigonometric formulas and the α angle obtained from the TraumaCad® simulation

($r = 0.87$, $p < 0.0001$). A high correlation was also found between the β angle obtained with trigonometric formulas and the β angle obtained from the TraumaCad® simulation ($r = 0.88$, $p < 0.0001$).

DISCUSSION

The primary aim of this study was to analyse and quantify the influence of lower limb positioning in terms of hip abduction and adduction on the main methods of measuring JLO. The main finding was that JLOA was significantly affected by the position of the lower limb when acquiring long-leg weightbearing X-rays, in particular by the degree of hip abduction/adduction in the coronal plane, thereby confirming the initial hypothesis of the study. By using both trigonometric formulas and a dedicated software for preoperative planning (TraumaCad®), the authors simulated the MAX-ADD representing an ideal monopodal stance, the bipedal adduction angle (BIP-ADD) corresponding to the weightbearing bipedal stance, and the maximum abduction angle (MAX-ABD) corresponding to an abduction equal to the MAX-ADD. The variation of the JLOA from the NEU position to the MAX-ADD position was on average 6.4 ± 0.5°. The variation of the JLOA from the MAX-ADD position to the MAX-ABD position was 12.8 ± 0.9°.
Several in vitro and clinical studies highlighted the importance of knee JLO in the preoperative planning of the osteotomies around the knee and TKR together with its role in affecting the outcomes of these procedures. Feucht et al. [10] simulated knee osteotomy on over 300 long-leg weightbearing radiographs of patients with varus malalignment. The authors found that, if anatomic correction (postoperative MPTA ≤ 90°) was intended, only 12% of patients could be corrected via isolated HTO, whereas 63% required a double-level osteotomy. If slight overcorrection was accepted (postoperative MPTA ≤ 95°), 57% of patients could be corrected via isolated HTO, whereas 33% required a double-level osteotomy. Nakayama et al. [25], in a three-dimensional (3D) finite element study, showed that excessive obliquity of the joint line (>5°) after opening wedge high tibial osteotomy (OWHTO) resulted in higher shear forces on the tibial articular cartilage. In addition to these in vitro studies, several clinical papers investigated the role of postoperative knee JLO on the outcomes of HTO. The role of postoperative JLO in affecting the outcomes of HTO is still controversial, with some papers reporting inferior outcomes for patients with increased JLO [1, 19, 30] and other studies showing no influence of JLO on HTO results [11, 20, 27, 36]. Some of these studies, mostly those finding a negative correlation between excessive JLO and outcomes, are not without limitations. These limitations were highlighted by Rosso et al. [27] and included, among others: (1) a nonstandardized method for evaluating JLO and (2) using methods affected by hip abduction/adduction (i.e., JLOA).
Despite these controversies, some authors advocated the need for double-level osteotomies in order to avoid excessive JLO changes [10, 29]. In addition, some expert opinion papers arbitrarily set JLO cut-offs that should be considered as unacceptable postoperatively: JLO angle >4° [5], MJLA > 94°, and mechanical MPTA (mMPTA) > 95° [24].
JLO evaluation is also crucial in TKR. The adoption of techniques such as kinematic and functional alignment has also brought greater attention to the analysis and preservation of the joint-line inclination [12, 22, 35]. Clark et al. [8] showed that maintaining an unchanged joint line, especially in patients with constitutional varus, led to better outcomes after TKR. Sappey-Marinier et al. [28] reported similar results, demonstrating that TKR with mechanical alignment generally led to changes in JLO and inferior outcomes compared to patients with unchanged JLO. Also Bae et al. [6] suggested that alignment and JLO affected the long-term survival rate of patients who underwent TKA.
Based on the data mentioned above, sports medicine and total joint surgeons are increasingly paying more attention not to excessively alter JLO after surgery. This has a significant clinical impact on the indications of one procedure over another as well as on the invasiveness and costs of the surgeries. However, these new trends in knee surgery are not supported by strong evidence. One of the reasons for this insufficient evidence can be identified in the lack of standardized methods for

JLO assessment and the use of methods that are significantly affected by hip position, as the JLOA. JLOA is one of the most commonly used methods to assess knee JLO. In the present paper, the authors showed a significant variability of JLOA based on the position of the hip, raising some concerns regarding the results of the papers using JLOA as an independent variable as well as some of the cut-offs proposed in the literature for acceptable JLO.

These concerns regarding the need for a reliable method for JLO measurement have been previously raised by other studies, using different methodological approaches compared to the present paper. Xie et al. [37], in a recent cross-sectional study, compared different methods described in the literature for assessing JLO [4, 17, 20, 26, 34]: JLOAF (angle between a line tangent to femoral condyles and the ground), JLOAM (angle between the bisector of JLCA and the ground), JLOAT (angle between a line tangent to the tibial plateau and the ground), MJLA and MPTA (as previously described in the present article). Every method tested, except for MPTA, was affected by position of the hip, with JLOA being affected the most. As a limitation of the study, the authors mentioned that some rotation differences (between bipedal and monopodal X-rays) could be present at filming and affect the radiographic measurements. Lee et al. [21] studied the effect of foot position during long leg X-ray acquisition on JLOA in 92 patients after TKA. The authors concluded that JLOA changed by 3.7° per 100 mm of distance between the feet. Other studies investigated the role of different types of imaging and demonstrated that alignment determined by LLRs underestimates the magnitude of both constitutional varus alignment and JLO compared to CT [32].

In the present study, the authors preferred the use of trigonometric formulas and digital software simulation to avoid possible confounding factors (i.e., different rotation during X-ray acquisition in different hip positions). In addition, with the methods described in the present study, the theoretical changes of the JLOA could be precisely determined, independently of foot distance and patient's size (i.e., height, femoral head–pubic symphysis distance, and tibial width at the ankle). As another strength, hip, ankle and subtalar joint compensation on the JLO was not a confounding factor in the present study. In fact, different papers showed the mitigating effects of hip, ankle and subtalar joints compensation on knee JLO. Bartholomeeusen et al. [7] demonstrated that the ultimate postoperative JLO after HTO does not only depend on the size of correction, but was a complex interaction between foot/knee position and size of correction. Kim et al. [18] showed that after HTO the difference between pre-operative and postoperative knee JLO was on average 3.8° ± 2.6°, and this was on average 2.6° less than the pre- and postoperative MPTA difference. The authors concluded that this phenomenon was due to hip and ankle joint compensation (hip adduction and ankle valgisation).

The main limitation of the present study is that the results obtained are based on trigonometric formulas and simulations using a dedicated digital software and not on different X-rays obtained at different degrees of hip adduction. In addition, these simulated measurements do not replicate the possible rotation of the knee joint during adduction and abduction. However, obtaining different long leg X-rays on the same patients with different degrees of hip adduction would entail excessive and unjustified dose of radiation as well as the possibility of rotational differences at filming. Perhaps by using low-dose, weight-bearing X-ray technology such as EOS imaging, it would be possible to perform these measurements in real life and compared them with the results obtained from our simulation. As another limitation, the measurements described in the present study are obtained in a static setting and not during walking. This is a well-described limitation of all studies regarding knee JLO. However, in the present study, the MAX-ADD position (center of the ankle under the pubic symphysis) simulated the position of the limb during ambulation. Nevertheless, further studies are needed with the goals of (1) investigating the JLO changes in a dynamic setting and (2) understanding the role of hip, ankle and subtalar joint in mitigating JLO.

The obliquity of the joint line is a dynamic concept, with an average inclination of 3° of varus in a physiologically aligned limb, as a result between knee articular geometry and the distance between the hip joint center and the ankle joint center. During gait, a single-limb stance phase occurs (stance phase), generating an adduction moment. This results in the formation of a joint-line parallel to the ground (0° of inclination), thereby generating a more uniform distribution of joint forces between the medial and lateral compartments of the knee [14]. Our results showed that the difference of the JLOA from a neutral lower limb position to the monopodal stance position can reach up to 6°, a value that exceeds the cut-off points for physiological knee JLO described in the literature. Therefore, it is essential to identify the most accurate measurement method that is least affected by the position of the lower limb in space to assess the true obliquity of the joint line and its variations.

CONCLUSIONS

In conclusion, JLO angle is significantly influenced by the degree of adduction or abduction of the lower limb. This angle should not be used as it is, without considering the degree of hip adduction/abduction. Alternative measurement methods, such as the MJL angle, should be preferred during preoperative evaluation as they are minimally affected by hip and ankle position.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Marco Bechis, Antonino Cantivalli and Francesco Liberace. The first draft of the manuscript was written by Marco Bechis and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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CONFLICTS OF INTEREST STATEMENT

Davide E. Bonasia: Arthrex Inc; Paid presenter or speaker; The Knee journal Editorial or governing board; SIAGASCOT: Board or committee member. Roberto Rossi: American Association of Hip and Knee Surgeons: Board or committee member; Angelini Farmaceutica: Paid presenter or speaker; Arthrex Inc; Paid presenter or speaker; DePuy, A Johnson & Johnson Company: Paid presenter or speaker; Knee Society: Board or committee member; Lima corporate: IP royalties; Zimmer: Paid consultant; Paid presenter or speaker. Federica Rosso: Medacta: Other financial or material support. The remaining authors declare no conflict of interest. All authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest or nonfinancial interest in the subject matter or materials discussed in this manuscript.

ETHICS APPROVAL

Ethical approval was waived by the local Ethics Committee of University of Turin in view of the retrospective nature of the study and all the procedures being performed were part of the routine care.

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Table 1. Main demographic characteristics and deformity analysis of patients enrolled in this study.

Gender	**Male (*n*)**	**Female (*n*)**	
	57	**43**	
Age	**Mean (years)**	**SD (years)**	
	57.6	**5.2**	
Radiographical measurements		**Mean (°)**	**SD (°)**
HKA		**178**	**5.2**
MPTA		**86.5**	**2.4**
LDFA		**88.2**	**2.8**
JLCA		**1.4**	**1**
JLOA (RadiaAnt)		**1.2**	**2.3**
JLOA (TraumaCad)		**1**	**2**
MJLA (RadiaAnt)		**87.6**	**2**
MJLA (TraumaCad)		**88**	**2**
ALPHA angle (Formulas RadiAnt)		**6.4**	**0.5**
ALPHA angle (TraumaCad)		**6**	**1**
BETA angle (Formulas RadiAnt)		**4.6**	**0.4**
BETA angle (TraumaCad)		**5**	**1**

Note: Values are presented as mean and standard deviation (SD) in degrees. Abbreviations: HKA, hip-knee-ankle angle; JLCA, joint line congruency angle; JLOA, joint line obliquity angle; LDFA, lateral distal femoral angle; MJLA, Mikulicz joint line angle; MPTA, medial proximal tibial angle.

Table 2. Intra- and interobserver reliability for the measurements.

Measure	Intraobserver (Rater 1)		Intraobserver (Rater 1)		Interobserver (ICC)				Interobserver (Kappa)		
	Coeff. R	*p*-Value	Coeff. Rho	*p*-Value	Coeff. same	95% confidence interval (CI) same	Coeff aver	95% CI aver	Kappa	SD	95% CI
Center of the femoral head—pubic symphysis distance (mm)	**NA**	**NA**	**0.99**	**<0.0001**	**0.98**	**0.96–0.98**	**0.99**	**0.98–0.99**	**0.85**	**0.02**	**0.80–0.90**
Center of the femoral head—center of the ankle distance (mm)	**0.99**	**<0.0001**	**NA**	**NA**	**0.99**	**0.99–0.99**	**0.99**	**0.99–0.99**	**0.96**	**0.01**	**0.95–0.97**
Center of the ankle—medial malleolus dista	**0.99**	**NA**	**0.89**	**<0.0001**	**0.45**	**−0.09 to 0.74**	**0.62**	**−0.19 to 0.84**	**0.25**	**0.06**	**0.12–0.37**

Measure	Intraobserver (Rater 1)		Intraobserver (Rater 1)		Interobserver (ICC)				Interobserver (Kappa)		
	Coeff. R	*p*-Value	Coeff. Rho	*p*-Value	Coeff. same	95% confidence interval (CI) same	Coeff aver	95% CI aver	Kappa	SD	95% CI
nce (mm)											
ALFA angle (°)	0.99	<0.0001	NA	NA	0.98	0.97–0.99	0.99	0.98–0.99	0.89	0.02	0.86–0.93
BETA angle (°)	0.97	<0.0001	NA	NA	0.87	0.29–0.96	0.93	0.45–0.98	0.63	0.05	0.53–0.73
HKA (°)	NA	NA	0.99	<0.0001	0.98	0.96–0.99	0.99	0.98–0.99	0.84	0.03	0.78–0.89
MPTA (°)	0.99	<0.0001	NA	NA	0.74	0.56–0.85	0.85	0.71–0.92	0.67	0.07	0.53–0.80
LDFA (°)	0.99	<0.0001	NA	NA	0.91	0.80–0.95	0.95	0.89–0.98	0.74	0.05	0.65–0.83
JLCA (°)	NA	NA	0.98	<0.0001	0.82	0.70–0.90	0.90	0.82–0.95	0.57	0.07	0.44–0.70
JLOA (°)	0.99	<0.0001	NA	NA	0.96	0.93–0.98	0.98	0.96–0.99	0.80	0.03	0.75–0.86
MJLA (°)	0.99	<0.0001	NA	NA	0.87	0.78–0.93	0.93	0.88–0.96	0.67	0.05	0.58–0.77

Abbreviations: HKA, hip-knee-ankle angle; JLCA, joint line congruency angle; JLOA, joint line obliquity angle; LDFA, lateral distal femoral angle; MJLA, Mikulicz joint line angle; MPTA, medial proximal tibial angle.

Figure 1

Alignment evaluation. (a) The hip-knee-ankle angle (HKA) is shown on the right limb with red lines; this is the angle between a line from the center of the femoral head to the center of the knee and the line from the center of the knee to the center of the ankle. The adduction angle is shown on the left limb with green lines; this is the angle between the Mikulicz line and a line perpendicular to the ground. (b) The lateral distal femoral angle (LDFA) is shown with purple lines: angle between a line tangent to femoral condyles and the mechanical axis of the femur, measured on the lateral side. The medial proximal tibial angle (MPTA) is shown with orange lines: angle between a line tangent to tibial plateau and the mechanical axis of the tibia measured on the medial side. The joint-line congruency angle (JLCA) is shown with black dotted lines: angle between a line tangent to distal femoral condyles and a line tangent to the proximal tibial condyles.

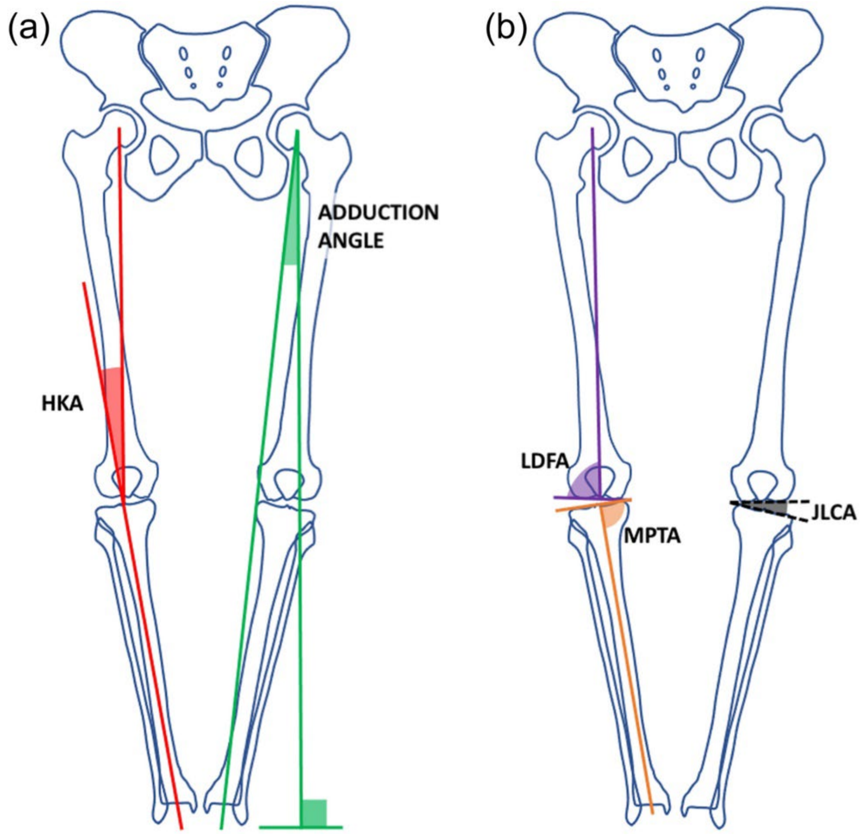

Figure 2

The knee joint-line obliquity evaluation. (a) Joint-line obliquity angle (JLOA), shown with red lines, is the angle between a line tangent to the proximal tibial plateau and the horizontal line of the ground. (b) Mikulicz joint line angle (MJLA), shown with green lines, is the angle between the bisector of the JLCA and the Mikulicz line measured on the medial tibial side. (c) Medial proximal tibial angle (MPTA), shown with orange lines, is the angle between a line tangent to tibial plateau and the mechanical axis of the tibia measured on the medial side.

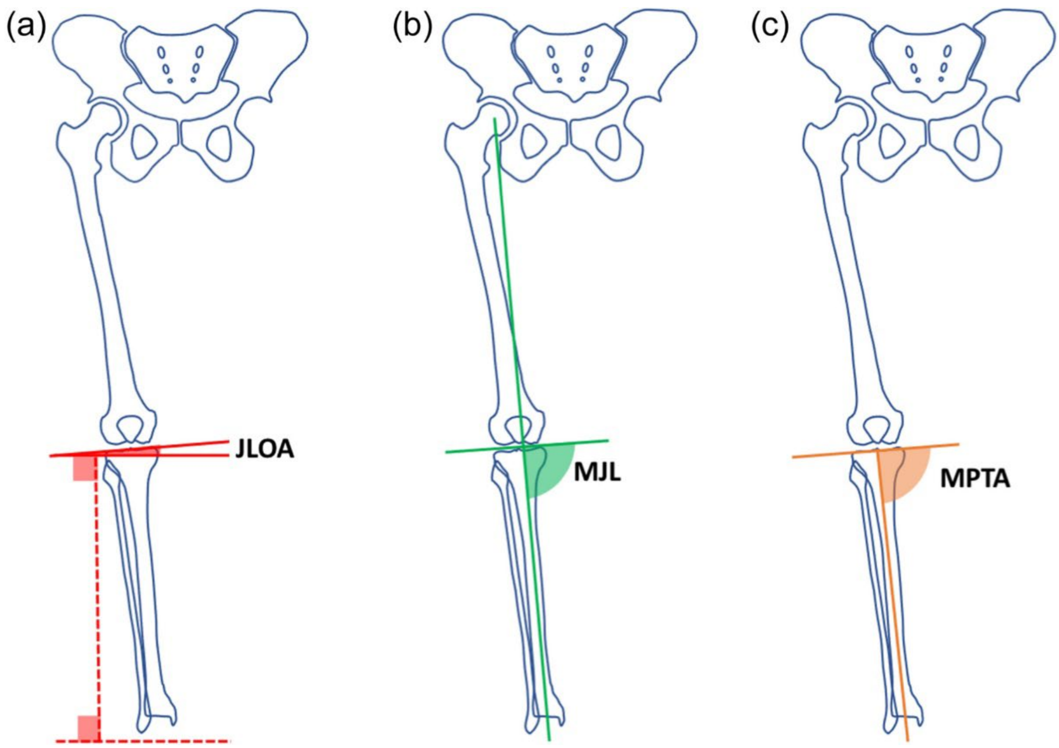

Figure 3

The 4 different positions of the lower limb considered, based on the hip abduction/adduction. (a) Neutral position (NEU) with the center of the ankle joint under the center of the femoral head; (b) weightbearing bipedal stance position (BIP-ADD) with legs together (right and left medial malleoli touching each other); (c) weightbearing monopodal stance position (MAX-ADD) with the center of the ankle under the pubic symphysis; (d) maximum abduction position (MAX-ABD) the hip abducted of the same angle calculated for the maximum adduction position.

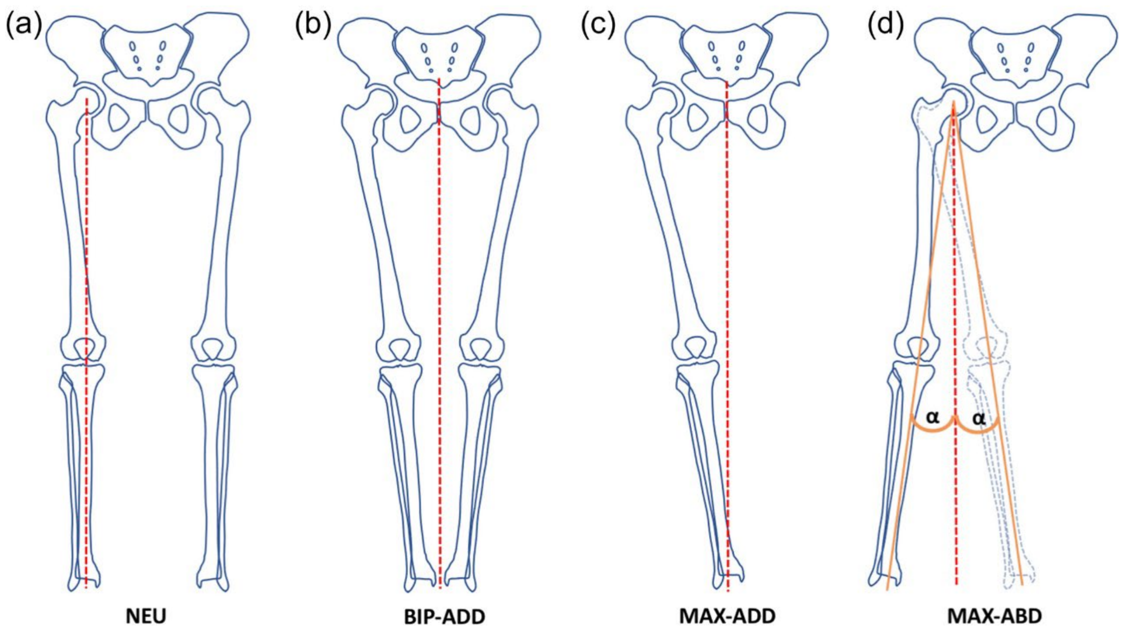

Figure 4

Schematic representation of linear measurements and simulation different limb positions. (a) *a* = distance between the center of the femoral head and the pubic symphysis; *b* = distance between the center of the femoral head and the center of the ankle; *c* = distance between the center of the ankle and the medial malleolus. (b) Angle *β* was defined as bipedal adduction angle (BIP-ADD) and calculated with the formula $\beta = \arcsin((a - c)/b)$. (c) Angle *α* was defined as the maximum adduction angle (MAX-ADD), as in a perfect monopodal stance, and calculated with the formula $\alpha = \arcsin(a/b)$. (d) In order to obtain the total possible variation from the MAX-ADD position to the MAX-ABD position, the *α* angle was multiplied by 2.

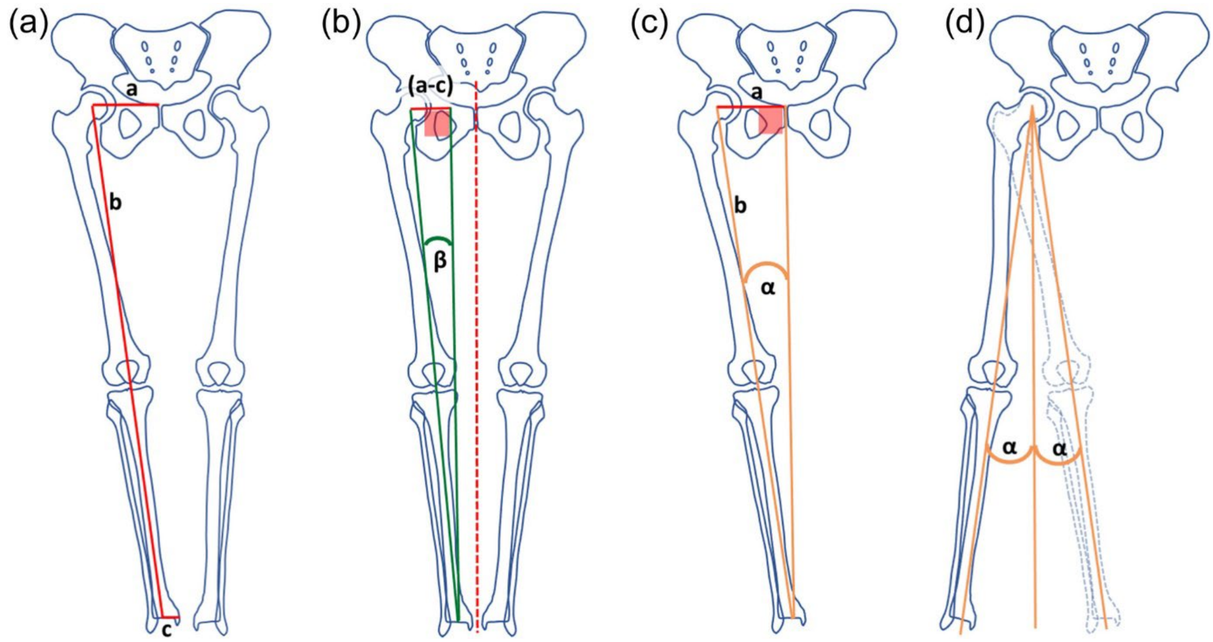

Figure 5

Schematic representation of angular measurements and simulation different limb positions. It was assumed that angles α and β do not only represented the degree of lower limb adduction, but also the variation of the joint line obliquity angle (JLOA) with respect to the limb in neutral (NEU) position. (a) joint-line obliquity angle (JLOA) with the limb in neutral (NEU) position. (b) In the weightbearing bipedal stance position (BIP-ADD) the limb is adducted of the β angle and the JLOA is increased of the β angle with respect to the limb in NEU position. (c) In the weightbearing monopodal stance position (MAX-ADD) the limb is adducted of the α angle and the JLOA is increased of the α angle with respect to the limb in NEU position. (d) In the maximum abduction position (MAX-ABD) the limb is abducted of the α angle and the JLOA is decreased of the α angle with respect to the limb in NEU position.

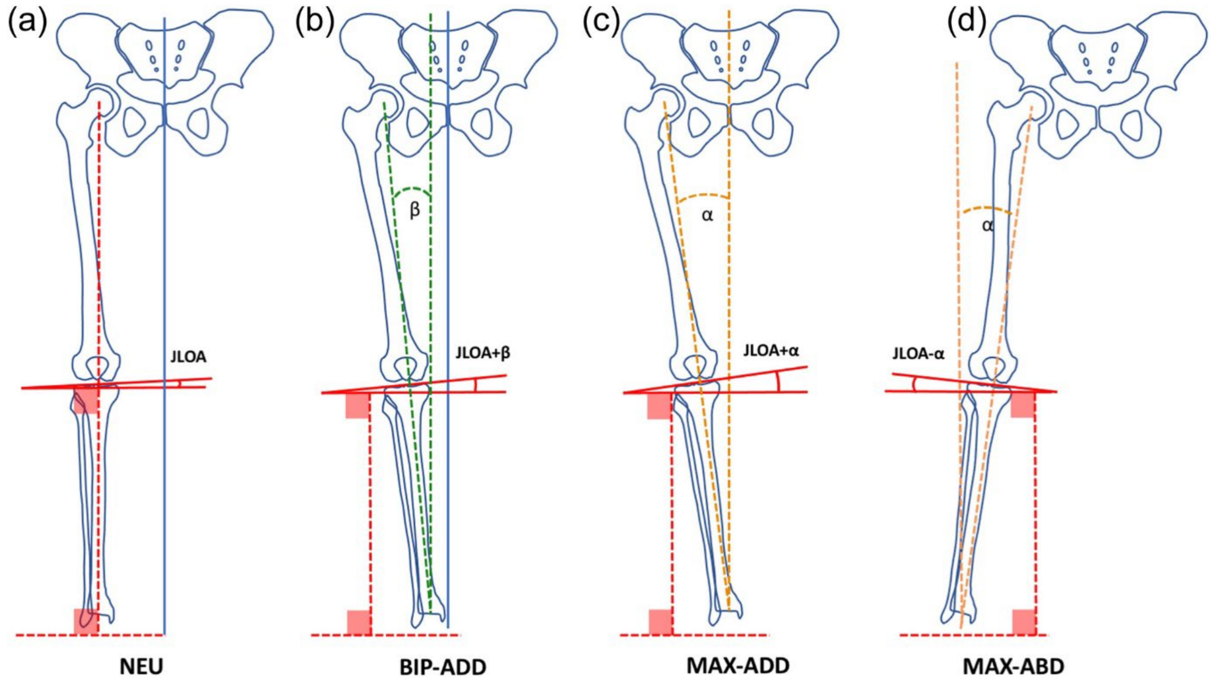

Figure 6
Simulation of the four different positions of the lower limb with TraumaCad® digital software, based on the hip abduction/adduction. (a) Neutral position (NEU) with the center of the ankle joint under the center of the femoral head; (b) weightbearing bipedal stance position (BIP-ADD) with legs together (right and left medial malleoli touching each other); (c) weightbearing monopodal stance position (MAX-ADD) with the center of the ankle under the pubic symphysis; (d) maximum abduction position (MAX-ABD) the hip abducted of the same angle calculated for the maximum adduction position.

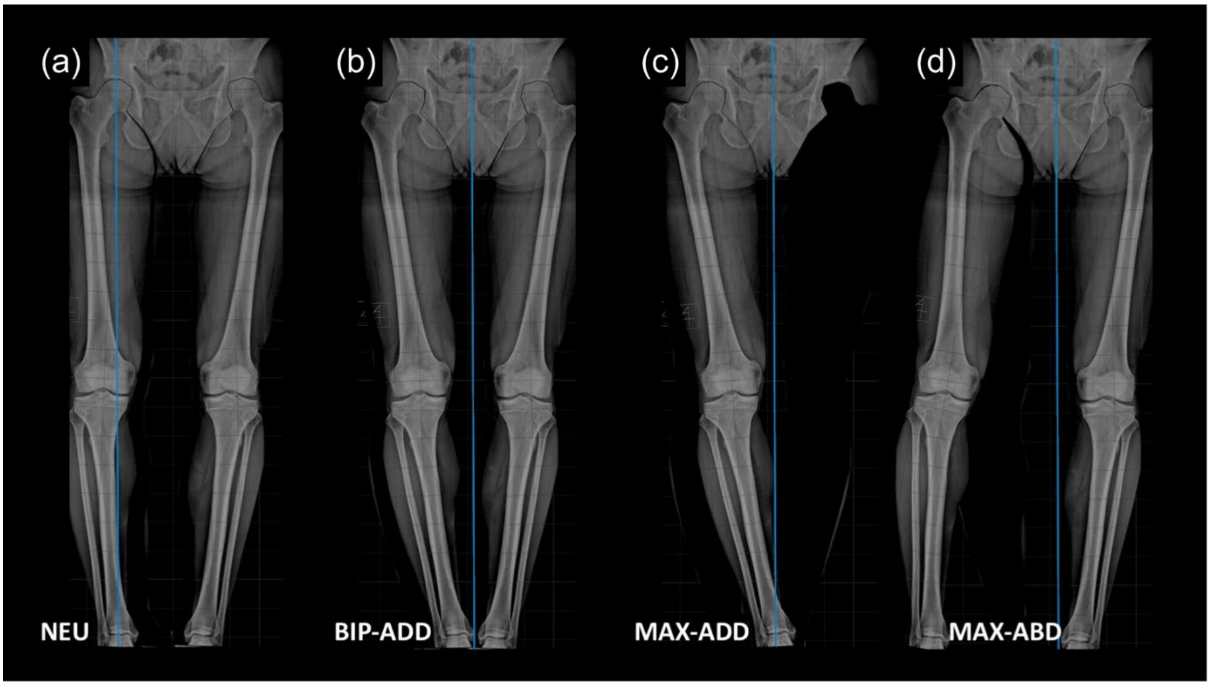

Figure 7

The knee joint-line obliquity evaluation with TraumaCad® digital software. (a) Joint-line obliquity angle (JLOA), shown with red lines, is the angle between a line tangent to the proximal tibial plateau and the horizontal line of the ground. (b) Mikulicz joint line angle (MJLA), shown with green lines, is the angle between the bisector of the JLCA and the Mikulicz line measured on the medial tibial side.

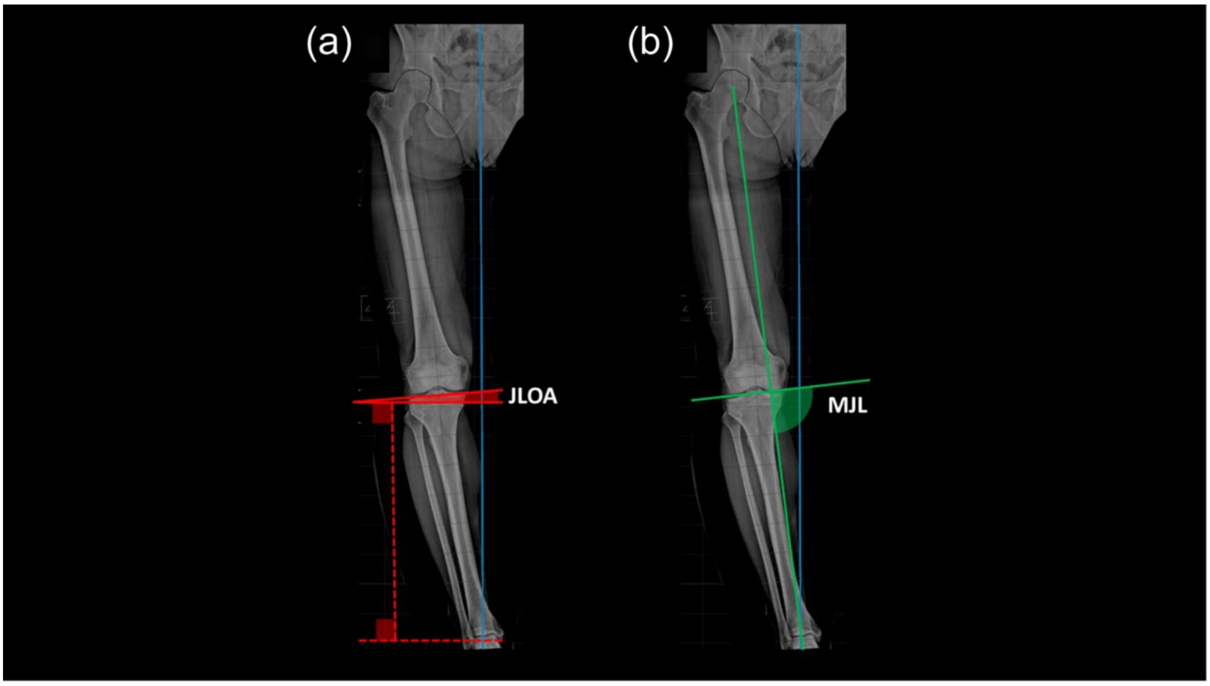

Figure 8
The strengthening the reporting of observational studies in epidemiology (STROBE) diagram for inclusion process.