



Patient-specific prediction of joint line convergence angle after high tibial osteotomy using a whole-leg radiograph standing on lateral-wedge insole

Yukio Akasaki¹ · Hideki Mizu-uchi¹ · Satoshi Hamai¹ · Hidetoshi Tsushima¹ · Shinya Kawahara¹ · Tomohiro Horikawa² · Yasuharu Nakashima¹

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Abstract

Purpose To assess the usefulness of a whole-leg radiograph standing on lateral-wedge insole (LWI) for predicting the change in joint line convergence angle (JLCA) before vs. after high tibial osteotomy (HTO).

Methods Forty knees with medial osteoarthritis underwent open-wedge HTO. Pre-operatively, all patients had whole-leg radiographs taken in three different conditions: supine, standing, and standing on LWI inclined at 20°. A standing whole-leg radiograph was also obtained post-operatively. Radiological measurements including JLCA and percentage of mechanical axis (%MA) were compared. Using pre-operative radiographs, correction angles were calculated with the target %MA at 62.5%. Correlations between the difference in calculated correction angle among the three pre-operative conditions and the change in JLCA before vs. after HTO were assessed.

Results In the pre-operative standing conditions, the mean JLCA of 3.8° was significantly decreased to 3.2° using LWI, which did not differ from post-operative JLCA of 3.1°. Mean %MA significantly shifted laterally from 20.6 to 24.8% using LWI, and was strongly correlated with the change in JLCA (coefficient, 0.83). Calculated correction angles differed significantly among the three pre-operative conditions. The difference in calculated correction angle between standing with and without LWI was strongly correlated to the change in standing JLCA before vs. after HTO (coefficient, 0.73).

Conclusion Larger differences in calculated correction angles between pre-operative radiographs standing with and without LWI predicted larger changes in JLCA after HTO. Whole-leg radiograph standing on LWI is a promising modality for correct pre-operative planning considering patient-specific changes in JLCA before vs. after HTO.

Level of evidence IV.

Keywords Osteoarthritis · Joint line convergence angle · JLCA · High tibial osteotomy · HTO · Lateral-wedge insole · Whole-leg radiograph

Abbreviations

JLCA Joint line convergence angle
HTO High tibial osteotomy
LWI Lateral-wedge insole
HKAA Hip–knee–ankle angle
%MA Percentage of mechanical axis

LDFA Lateral distal femoral angle
MPTA Medial proximal tibial angle

Introduction

The change in joint line convergence angle (JLCA) after high tibial osteotomy (HTO) is one of the most relevant factors for unexpected post-operative outliers of leg alignment [1, 12, 16, 19, 23, 26, 29]. Knee adduction moment [27, 29] and soft-tissue laxity [16, 19, 23] play crucial roles in determining the change in JLCA before and after HTO in the standing position. Importantly, the impact of these factors depends on the specific characteristics of each patient;

✉ Yukio Akasaki
akasaki@ortho.med.kyushu-u.ac.jp

¹ Department of Orthopaedic Surgery, Kyushu University, 3-1-1, Maidashi, Higashi-ku, Fukuoka 812-8582, Japan

² Department of Orthopaedic Surgery, Omuta Tenryo Hospital, 1-100, Tenryomachi, Omuta 836-8566, Japan

therefore, it is difficult to predict pre-operatively how much JLCA will change after HTO.

A lateral-wedge insole (LWI) can effectively reduce knee adduction moment in patients with medial compartmental osteoarthritis [1, 2, 13, 30], resulting in a lateral shift of the mechanical axis [30]. Therefore, it was hypothesized that pre-operative JLCA on standing with LWI could be similar to the post-operative JLCA on standing after HTO. If that is the case, a whole-leg radiograph standing on LWI would be useful for the more precise calculation of correction angle in the patients who have the potential change in JLCA after HTO in the standing position.

The purpose of this study was to determine whether pre-operative JLCA standing on LWI would mimic post-operative JLCA after HTO, in comparison with conventional supine and standing conditions. Subsequently, the usefulness of a whole-leg radiograph standing with LWI for pre-operative planning of HTO was evaluated.

Patients and methods

Patient recruitment

This study retrospectively analyzed 40 knees with medial osteoarthritis with Kellgren–Lawrence grade II ($n = 16$), III ($n = 17$), or IV ($n = 7$) that underwent open-wedge HTO at Kyushu University Hospital. All patients who had pre-operative whole-leg radiographs while supine, standing, and standing on LWI were included. The study population comprised 18 men and 22 women, with a mean age of 60.3 ± 8.8 (range 39–74) years. The indication for surgery was varus deformity with persistent pain at the medial side of the knee after at least 3 months of conservative treatment. None of the patients had anterior or posterior cruciate ligament deficiency or post-traumatic bony deformity or flexion contracture $> 10^\circ$.

Pre-operatively, all patients had whole-leg anteroposterior radiographs of the operative limb taken while supine, standing, and standing on LWI (Fig. 1); the images were all acquired on the same day (Fig. 2a). LWI was originally designed and manufactured for this study (Olympus Terumo Biomaterials Corp., Tokyo, Japan). The main board of LWI consisted of polyethylene of 15 mm thickness which is undistortable by 80 kg force. Butadiene rubber was affixed for slip resistance. The inclination was easily adjustable to 10° , 15° , and 20° (Fig. 1) by the replacement of base height. Under the opposite foot, a stepboard of the same height as LWI was placed. In this study, the incline of the lateral wedge was set at 20° because the initial ten patients felt knee load shifted to lateral consistently, comparing with 10° and 15° . A standing whole-leg radiograph was also obtained 3–6 months after HTO (Fig. 2c).

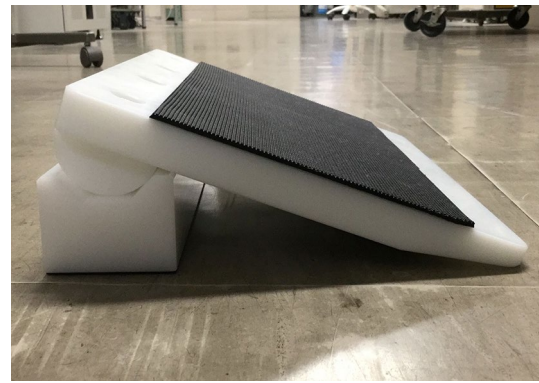


Fig. 1 Lateral wedge insole inclined at 20°

Radiological measurements

Radiograph images were acquired by the picture archiving and communication system and imported into a digital imaging software (OP-A, FUJIFILM medical, Japan) that measures distance and angle to one decimal place. Hip–knee–ankle angle (HKAA), percentage of mechanical axis (%MA), lateral distal femoral angle (LDFA), medial proximal tibial angle (MPTA), and JLCA were measured. If leg alignment was varus, HKAA was recorded as positive (+). If the apex of the JLCA was medial, it was recorded as positive. The difference between pre- and post-operative JLCA was expressed as Δ JLCA (post–pre). To determine test–retest reliability, all radiographic assessments were performed twice at intervals of more than 2 weeks. The test–retest reliabilities of all radiographic measurements were evaluated using intraclass correlation coefficients.

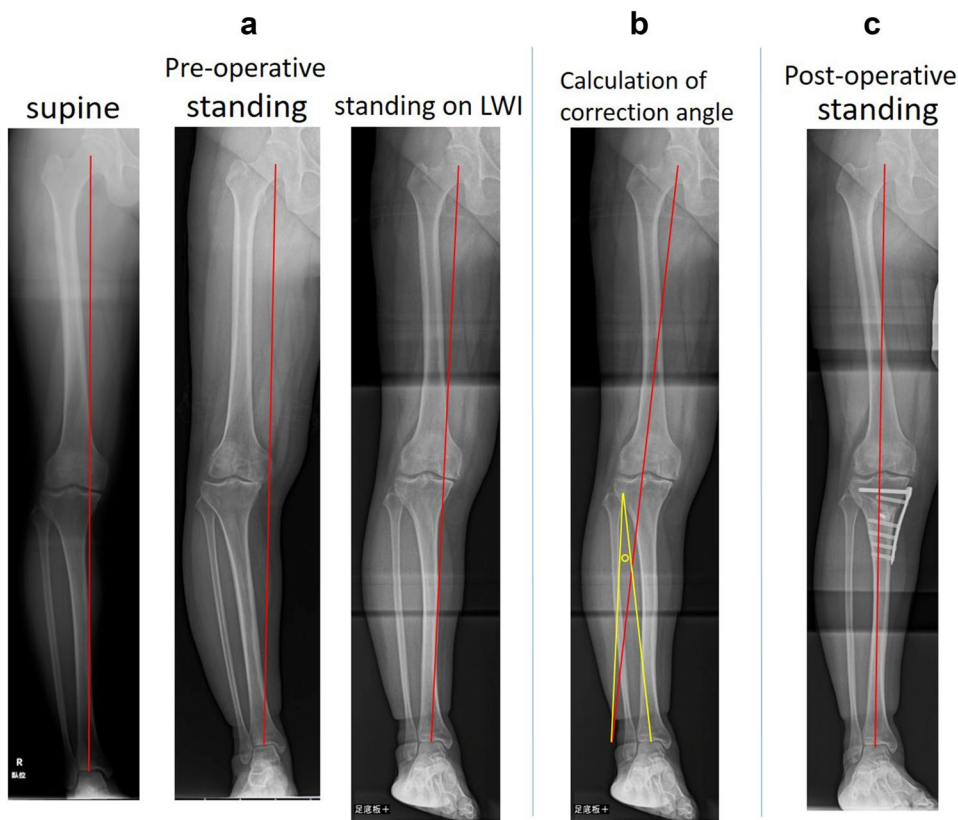
Calculation of correction angle using three different pre-operative radiographs

In pre-operative planning, correction angle was calculated by the modified Miniaci method described by Elson et al. [5] for opening wedge osteotomy, with the goal of achieving target alignment passing through 62.5% of %MA (Fig. 2b). The difference in calculated correction angle among the three different pre-operative conditions was expressed as Δ correction angle.

Surgical technique

A whole-leg radiograph standing on LWI was used for determining the effective degree of correction (Fig. 2b). Biplanar open-wedge osteotomy was conducted for all patients. The first osteotomy was performed obliquely from 3.5 to 4 cm below the medial joint line to the upper

Fig. 2 Representative whole-leg anteroposterior radiographs of the operative limb. **a** Pre-operative views while supine, standing, and standing on lateral-wedge insole (LWI). **b** Calculation of correction angle by the Miniaci method. **c** Post-operative view while standing



position of the proximal tibiofibular joint. The second frontal osteotomy was performed with retrotubercle ascending or descending cut procedure. After the planned wedge was opened and filled with bone substitute of beta-tricalcium phosphate, a locking plate (TriS Medial HTO Plate System®; Olympus Terumo Biomaterials Corp., Tokyo, Japan) was placed on the medial aspect of the tibia.

This study was approved by the institutional review board at Kyushu University Hospital (ID number of the approval: 28–366) as a retrospective study.

Statistical analysis

All measurements were normally distributed and expressed as means and standard deviations. Repeated-measure analysis of variance was conducted to compare differences among groups. Correlations between Δ correction angle among the three pre-operative conditions and Δ JLCA in standing before vs. after HTO were assessed using Spearman's rank correlation coefficient analysis. Statistical analyses were performed using JMP software version 14.2.0 (SAS Institute, Cary, NC, USA). $p < 0.05$ was considered to indicate statistical significance. In the power analysis, calculated sample size was 31 when the power of the study was 0.95 with an effect size of

0.61, which was determined based on the mean values and standard deviations of JLCA in pre-operative standing and standing on LWI.

Results

The test–retest reliabilities expressed as intra-rater reliability for measurements of %MA, HKAA, MPTA, LDFA, and JLCA were 0.99, 0.98, 0.99, 0.99, and 0.98, respectively.

Pre-operatively, there were significant differences in mean values of %MA, HKAA, and JLCA among the three conditions (Table 1). In the pre-operative standing conditions, %MA significantly shifted laterally when using a LWI, with an accompanying lateral shift of HKAA. The changes in %MA and HKAA in each patient were significantly correlated with the change in JLCA between standing with and without LWI ($R = 0.83$ and 0.79 , respectively). By contrast, the mean values of MPTA and LDFA were similar among three conditions (Table 1).

Mean JLCA in pre-operative supine and standing were significantly different from that in post-operative standing (Table 1). By contrast, there was no significant difference in JLCA between pre-operative standing on LWI and post-operative standing. Figure 3 shows the distributions of Δ JLCA values from each pre-operative condition and

Table 1 Radiographic measurements

	Pre-operative			Post-operative
	Supine	Standing	Standing on LWI	Standing after HTO
%MA	28.4 ± 8.9*	20.6 ± 13.5*	24.8 ± 10.1*	62.3 ± 8.8**
HKAA	4.6 ± 2.1*	6.4 ± 3.2*	5.5 ± 2.5*	-2.1 ± 2.5**
MPTA	85.4 ± 1.8	85.3 ± 1.9	85.4 ± 1.9	93.7 ± 2.1**
LDFA	87.9 ± 1.8	87.9 ± 2.1	87.8 ± 2.0	87.7 ± 2.3
JLCA	2.1 ± 1.5***	3.8 ± 2.0***	3.2 ± 1.5	3.1 ± 1.6
ΔJLCA to after HTO	1.1 ± 1.0*	-0.7 ± 1.0*	-0.1 ± 0.3*	N/A

Values are given as means ± standard deviation

LWI lateral-wedge insole, %MA percentage of mechanical axis, HKAA hip-knee-ankle angle, HTO high tibial osteotomy, LDFA lateral distal femoral angle, MPTA medial proximal tibial angle, JLCA joint line convergence angle, ΔJLCA difference in JLCA between pre- and post-operative conditions

*Significant difference among pre-operative conditions

**Significant difference relative to all pre-operative conditions

***Significant difference relative to standing after HTO

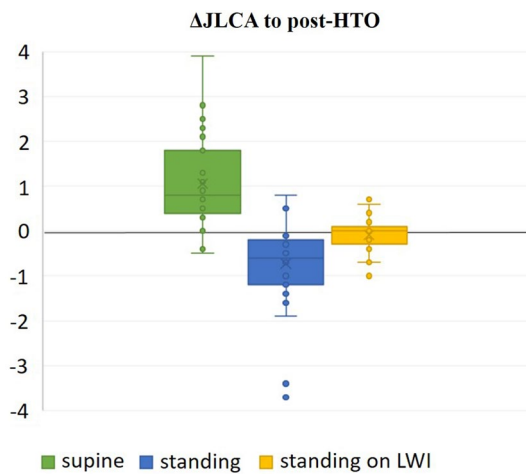


Fig. 3 The difference in pre- and post-operative joint line convergence angle (ΔJLCA) values from each pre-operative condition to the post-operative standing condition. LWI lateral-wedge insole, HTO high tibial osteotomy

post-operative standing. Standing on LWI yielded a smaller standard deviation than others, and the mean value was nearly zero.

Table 2 Calculated correction angles targeting 62.5% of %MA in the pre-operative setting

	Pre-operative		
	Supine	Standing	Standing on LWI
Calculated correction angle	8.3 ± 2.1*	10.3 ± 3.2*	9.3 ± 2.5*
Δcorrection angle to standing on LWI	-1.0 ± 1.4	1.0 ± 1.8	N/A
Δcorrection angle to standing	-2.0 ± 2.2	N/A	N/A

Values are given as means ± standard deviation

LWI lateral-wedge insole, Δcorrection angle difference of calculated correction angle

*Significant difference among pre-operative conditions

As a validation analysis, the simulated correction angles targeting 62.5% of %MA in the three pre-operative conditions, as determined by the Miniaci method, are shown in Table 2. Calculated correction angles differed significantly among the three conditions. The difference in value, Δcorrection angle, between standing with or without LWI was strongly correlated (coefficient, 0.73) to ΔJLCA while standing before vs. after HTO (Fig. 4a).

Discussion

The most important finding of this study was that the pre-operative JLCA on LWI mimicked the JLCA after HTO. In addition, prediction of patient-specific change in JLCA before vs. after HTO was feasible using a whole-leg standing radiograph on LWI, in two ways: direct measurement of JLCA values and subtraction of calculated correction angles between standing with and without LWI. In support of these findings, both %MA and HKAA effectively shifted laterally while standing on LWI. Furthermore, the magnitude of changes in these values was strongly correlated to

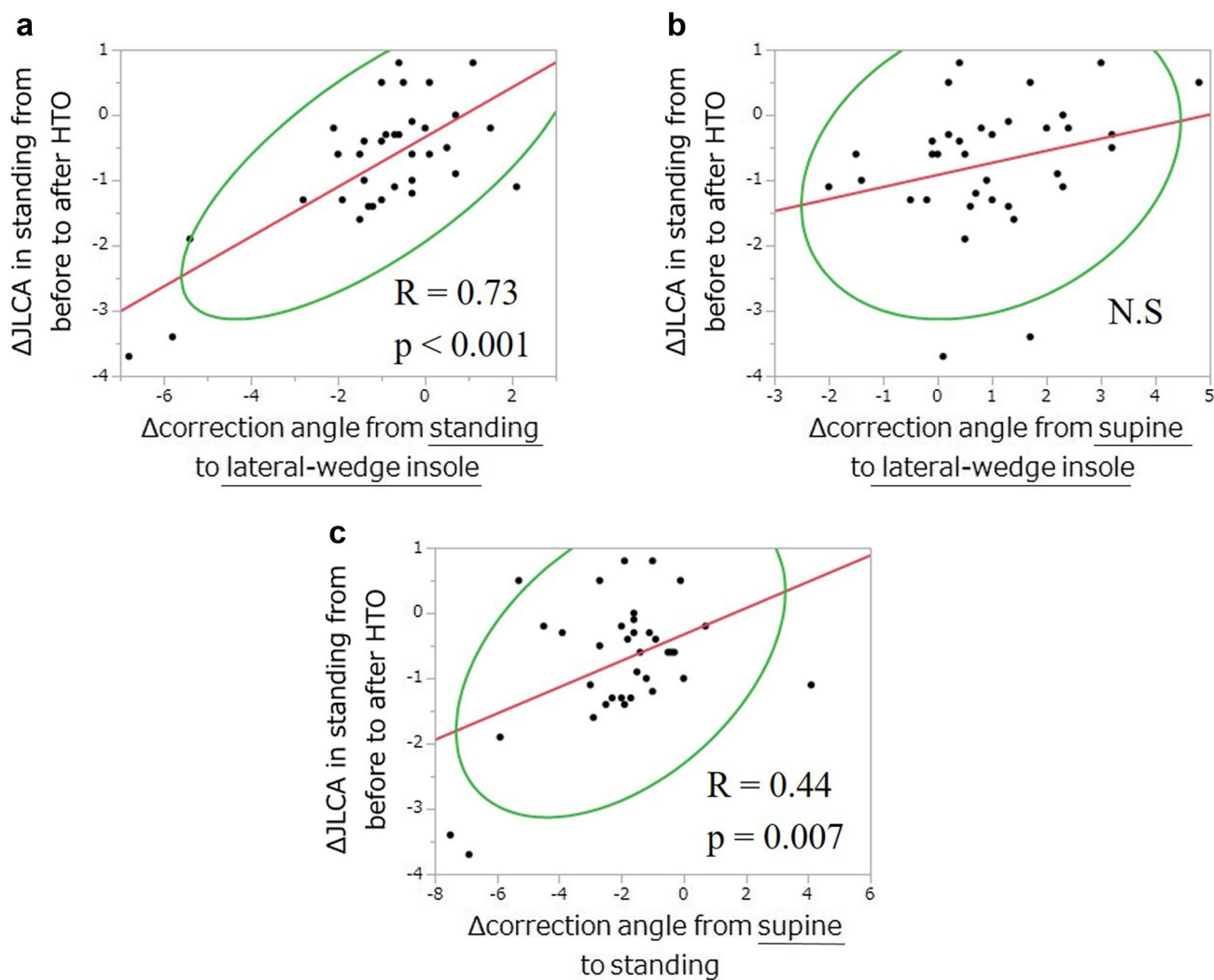


Fig. 4 Correlations between the difference in joint line convergence angle (Δ JLCA) in standing before vs. after high tibial osteotomy (HTO) and the difference in calculated correction angle, determined

by the Miniaci method (Δ correction angle), among three pre-operative conditions. Δ JLCA difference in JLCA between pre- and post-operative conditions, HTO high tibial osteotomy

those of the change in JLCA after HTO ($R=0.83$ and 0.79 , respectively).

Under- or over-correction in comparison to targeted leg alignment are associated with poorer clinical outcomes after HTO [4, 18, 28]. To avoid such outliers of post-operative leg alignment, various precision techniques, including the cable method and navigation-assisted surgery, have been developed to facilitate intraoperative visualization of the mechanical axis of the leg [8–10, 24]. These methods allow for real-time monitoring of leg alignment and achieving targeted correction, but can lead to unexpected post-operative outliers caused by the difference in JLCA between the non-weight and weight bearing status of the supine and standing positions [14, 15, 25, 31]. Consistent with this, the present study observed significant differences in JLCA between the supine and two standing conditions.

Considering that the change in JLCA before vs. after HTO is essential for pre-operative planning to achieve on-target post-operative alignment, several concepts related to the change in JLCA after HTO have been documented in previous studies [3, 17, 19, 23]. Dugdale et al. first proposed increasing pre-operative varus angulation due to slack lateral ligament and performed trigonometric analysis showing that each millimetre of lateral tibiofemoral surface separation caused about 1° of varus angular deformity, ultimately requiring subtraction in pre-operative calculations to avoid over-correction [3]. Recently, Ogawa et al. reported that pre-operative lateral laxity could be correlated with the change in JLCA after HTO, and generated a predictive formula showing that the change in JLCA increased by 0.59° for every 1° increase in pre-operative lateral laxity on a stress radiograph [23]. Lee et al. also reported a predictive formula

showing that post-operative JLCA increased by 0.6° per 1° increase in pre-operative medial laxity [17]. By contrast, the present study showed that standing on LWI could directly correct the lift-off of the lateral compartment caused by pre-operative knee adduction and laxity, and subsequently mimic the post-operative joint configuration along with lateral shift of the mechanical axis. This effect of LWI on the change in JLCA is definitely patient-specific, so there is no need to produce any predictive formula that fits all patients.

A whole-leg radiograph is an essential modality for calculating correction angle in pre-operative planning for HTO. Which weight-bearing condition is appropriate for correct planning is still unclear and remains optional for surgeons. Indeed, in this study, calculated correction angles using pre-operative whole-leg radiographs differed significantly among supine and standing with or without LWI. In the literature, Marti et al. proposed the usefulness of a whole-leg radiograph, corrected using a virtual axial push view of the knee, for calculating the correction angle [19]. This push view could expect the cartilaginous contact of the medial and lateral compartment simultaneously, however, yet non-weight bearing as measured on the varus and valgus stress radiographs. Under weight-bearing conditions in the present study, the difference in the calculated correction angle between standing with or without LWI was strongly correlated ($R=0.73$) to the change in JLCA before vs. after HTO. In other words, the larger difference in calculated correction angle between pre-operative standing with and without LWI predicted a larger change in JLCA after HTO while standing.

To date, the ideal post-operative alignment is still controversial, however, different post-operative valgus positions have been proposed per 5% in the %MA range from 50 to 65% based on the underlying pathology [6, 7, 11, 20–22]. Importantly, Feucht et al. demonstrated that 1° difference in leg alignment expressed as FTA could change 5% in the %MA [6]. Therefore, the precise prediction of the potential change in JLCA after HTO would be essential for achieving such individualized and pathology-based approach for the amount of axis correction [6, 11]. Using a whole-leg radiograph standing on LWI represents a promising approach for pre-operative planning, especially in the patients who have significant difference in calculated correction angle between pre-operative standing with and without LWI.

There were some limitations to this study. First, the sample size was relatively small. Nevertheless, in the post-hoc power analysis, an adequate power over 0.95 was calculated on the sample size of 40 patients. Second, LWI was expected to decrease knee adduction moment; however, the change in adduction moment was not actually measured. Third, only 20° of wedge inclination was used for radiography of this study to avoid exposure to unnecessary radiation. A further study would need to evaluate the effect of different inclinations on the pre-operative JLCA in standing. Finally,

surgical procedures such as medial soft tissue release may have affected the results.

Conclusion

Pre-operative JLCA in a whole-leg radiograph standing on LWI mimicked the post-operative JLCA after HTO. A larger difference in calculated correction angles between pre-operative radiographs standing with and without LWI predicted a larger change in JLCA after HTO. Thus, whole-leg radiograph standing on LWI represents a promising modality for correct pre-operative planning, considering patient-specific changes in JLCA before vs. after HTO.

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Compliance with ethical standards

Conflict of interest The authors state that there are no conflicts of interest which might have influenced the preparation of this manuscript.

Ethical approval Ethical approval was provided by the IRB of Kyushu University Hospital.

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