Higher Association of Pelvis-Knee Ankle angle compared with Hip-Knee-Ankle Angle with Knee Adduction Moment and Patient-Reported Outcomes after High Tibial Osteotomy

Abstract

Background: High tibial osteotomy (HTO) reduces the load distribution of the medial compartment by modifying leg alignment. Knee adduction moment (KAM), a surrogate measure of dynamic loading in the knee joint, decreases after HTO. However, leg alignment does not fully account for KAM.

Purpose: To assess the association between pelvis–knee–ankle angle (PKA), a novel radiographic parameter reflecting leg alignment and pelvic width, and KAM and patient-reported outcomes (PROMs) after HTO.

Study design: Cross sectional study

Methods: PKA is the angle between the line connecting the midpoint of the anterior superior iliac spine and the center of the knee joint and the mechanical axis of the tibia. Further, 54 patients with medial compartment knee osteoarthritis and varus alignment who underwent three-dimensional gait analysis preoperatively and 2 years after medial open-wedge HTO were evaluated. The primary outcomes were hip–knee–ankle angle (HKA), PKA, KAM peaks, and Knee Society Score (KSS). Single and multivariate regression analysis including PKA and KAM peaks as well as other demographic and radiologic factors was performed.

Results: HKA was weakly correlated with the first peak KAM ($r=-0.33$, $p<0.01$) and second peak ($r=-0.27$, $p=0.01$) before HTO, but not significantly correlated after HTO. PKA was moderately correlated with the first peak KAM ($r=-0.45$, $p<0.01$) and second peak ($r=-045$, $p < 0.01$) before HTO and with the first peak KAM ($r=-0.51$, $p < 0.01$) and second peak KAM ($r=-0.56$, $p<0.01$) after HTO. Multivariate linear regression revealed that postoperative PKA was still associated with the KAM peaks after HTO. Only postoperative PKA was correlated with the KSS satisfaction subscale ($r=-0.30$, $p=0.03$).

Conclusion: Although HKA was not correlated with KAM peaks after HTO, PKA was significantly correlated with KAM peaks in patients with varus knee osteoarthritis after HTO.

Clinical relevance: PKA can be a potential radiographic parameter in HTO planning with consideration of postoperative mediolateral load distribution.

Key Terms: high tibial osteotomy, knee, osteoarthritis, knee adduction moment, gait analysis

What is known about the subject: Leg alignment is associated with KAM. However, it does not fully account for postoperative KAM after HTO.

What this study adds to existing knowledge: The association between PKA, a novel radiographic parameter reflecting pelvic width and leg alignment, and postoperative KAM and PROMs was higher than that between PKA and leg alignment after HTO.

Introduction

Malalignment is a biomechanical factor associated with abnormal stress on the knee joint, which leads to knee osteoarthritis (OA).[11] Knee adduction moment (KAM) is a representative measure of the load distribution of the knee joint.[4, 25] That is because KAM is correlated with mediolateral load distributions[17, 25] and KAM is an important factor of knee OA progression[30] and severity.[35] The association between leg alignment and KAM was higher than that between KAM and other factors such as toe-out gait[3, 14, 17] and lateral body lean.[14, 31] Thus, KAM was not completely accounted for leg alignment.[14, 17]

Valgus high tibial osteotomy (HTO) is commonly used in the treatment of medial OA with varus alignment,[2, 12, 18] because HTO reduces the load distribution in the medial compartment by modifying leg alignment and slowing disease progression. KAM decreases after HTO,[7, 10, 33] and the change in leg alignment was associated with the change in KAM after HTO.[7, 26] However, a recent meta-analysis showed that the amount of alignment correction and postoperative valgus alignment were not correlated with reduced KAM after HTO.[22] A radiographic parameter highly correlated with KAM compared to leg alignment will be useful in HTO planning with consideration of mediolateral load distribution.

Moment is the product of the ground reaction force (GRF) and the moment lever arm. The GRF vector rises from the center of pressure toward the center of mass, which lies anterior to the second sacral vertebra in a one-leg standing position.[32] Given the correlations between the GRF vector and KAM lever arm and conventional mechanical axis (hip–knee–ankle angle [HKA], Figure 1), we hypothesized that a radiographic parameter reflecting both leg alignment and pelvic width could have a higher correlation with KAM lever arm and KAM than HKA. Thus, in this study, we developed a pelvis–knee–ankle angle (PKA), a novel radiographic parameter used in full-length standing radiographs and defined as the angle between the line connecting the midpoint of the anterior superior iliac spine and the center of the knee joint with the mechanical axis of the tibia (Figure 2).

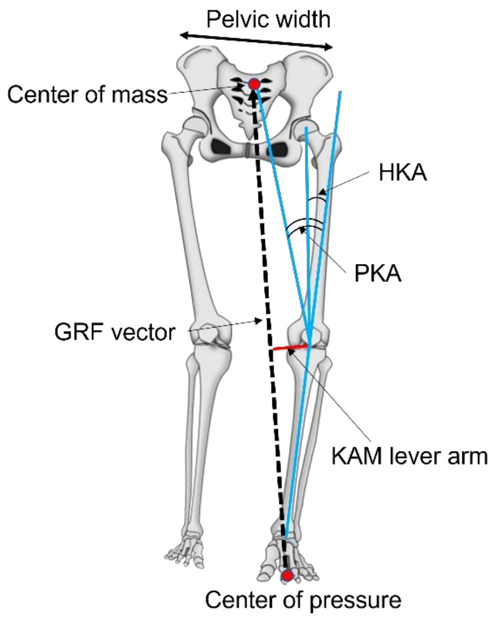

Figure 1. Schema depicting the association among the GRF vector, KAM lever arm, pelvic width, and HKA and PKA in a one-foot standing position. GRF, ground reaction force; KAM, knee adduction moment; HKA, hip–knee–ankle angle.

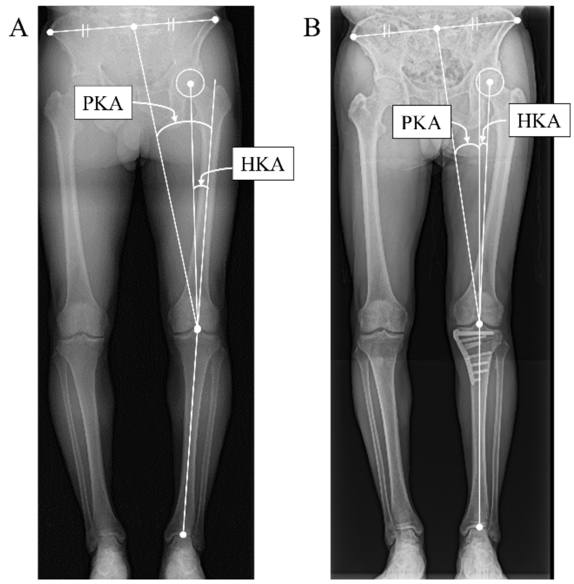

Figure 2. Radiographic parameters on a full-length standing radiograph. **A.** Valgus alignment. **B.** Varus alignment. Varus and valgus alignments were the negative and positive values of HKA, respectively. HKA, hip–knee–ankle angle; PKA, pelvis–knee–ankle angle; point S, defined as the midpoints of both the anterior superior iliac spines; line A, defined as the line connecting point S and the center of the knee joint; line B, defined as the line connecting the center of the knee joint and the ankle joint (referred to as the mechanical axis of the tibia); and PKA, defined as the smaller angle between lines A and B.

A current study aimed to assess the association between PKA and KAM and clinical outcomes in patients with varus knee OA before and after HTO. We hypothesized that PKA has a higher correlation with KAM than HKA before and after HTO.

Materials and methods

Study design

This study was approved by the institutional review board of (##), and informed consent was obtained from each participant. We retrospectively recruited all patients who underwent open-wedge HTO and gait analysis before and after HTO at ## from 2013 to 2017. The indications of open-wedge HTO in our hospital were moderate varus leg alignment (HKA angle of <−10°) and absence of moderate or severe OA in the patellofemoral joint and lateral compartment (Kellgren–Lawrence grade of <2).[21] The exclusion criteria included patients who did not provide informed consent and those who could not undergo gait analysis without a gait aid. Of the 78 patients who underwent HTO, 54 were finally included in the analysis (Table 1) (flow chart in the Supplemental File).

Table 1. Baseline demographic and clinical characteristics (n = 54)[α]

Characteristics	Values
Age, years	58.1 ± 6.1
Male/female sex, n	27/27
Height, cm	161.4 ± 8.1
Weight, kg	69.5 ± 9.2
BMI, kg/m^2	26.6 ± 2.8
HKA, degree	−4.0 ± 2.3
PKA, degree	15.1 ±2.2
MPTA, degree	84.4 ± 2.0
Kellgren–Lawrence grade 1/2/3/4	5/14/33/2

[α]Data were expressed as mean ± standard deviation unless otherwise stated.

BMI, body weight index; HKA, hip–knee–ankle angle; PKA, pelvic–knee–ankle angle; MPTA, medial proximal tibial angle

Varus alignment was the negative value of HKA.

Surgical procedure

All surgeries were performed by a senior orthopedic surgeon with 20 years of experience in performing knee surgery. The surgeon used the same operative technique, as described in a previous study,[19] with the open-wedge HTO system and a locking plate (Tomofix [DePuy Synthes, West Chester, PA, USA] or the TriS Medial HTO plate system [Olympus Terumo Biomaterials, Tokyo, Japan]). As reported in a previous study, the Miniaci method[28] was used in preoperative planning.[19] The intended angle of correction was calculated preoperatively to deliver a weight-bearing line of 62.5% of the tibial width, which is based on the magnitude of malalignment and status of the articular cartilage in the lateral tibiofemoral compartment.

Radiographic evaluation

The full-length standing anteroposterior radiograph images of the lower limb were taken with a long cassette while in the bipedal standing position, and they were used in the radiographic measurement. Each patient's foot position and digit direction on a radiolucent platform at the patella-neutral position were routinely recorded. Postoperative radiograph images were taken at the same foot position. To maintain the reproducibility of the radiographic evaluation, a bipedal standing radiograph was taken and foot position recording was performed. All radiographic images were digitally acquired using the picture archiving and communication system software (NEOVISTA I-PACS SX2, Konica Minolta Japan, Inc., Tokyo, Japan). Assessments were conducted using the software while controlling the magnification. The evaluation parameters were as follows: point S, defined as the midpoints of both the anterior superior iliac spines; line A, defined as the line connecting point S and the center of the knee joint; line B, defined as the line connecting the center of the knee joint and the ankle joint (referred to as the mechanical axis of the tibia); and PKA, defined as the smaller angle between lines A and B (Figure 2A). The varus and valgus alignments were the negative and positive values of HKA, respectively. HKA and PKA were measured before and 2 years after HTO.

Clinical evaluation

Clinical assessment was performed using the new Knee Society Score (KSS),[34] which was considered a patient-reported outcome measure (PROM) before and 2 years after HTO.

Gait analysis

As described in a previous study, three-dimensional gait analysis was performed before and 2 years after HTO.[29] Kinematic data were acquired using a three-dimensional motion capture system (RroRflex, Qualisys AB Inc., Gothenburg, Sweden) with eight infrared light cameras. Moreover, ground reaction forces during the tests were measured using two multicomponent force plates (OR6, Advanced Mechanical Technology Inc., Watertown, New York). Motion and force data were collected at 120 Hz. The three-dimensional knee kinematics were obtained using the point cluster technique.[5, 29] Reflective markers were placed on the lower limbs (56 markers) and the acromion on both sides.[29] An overabundance of markers (a cluster) was placed on each segment to minimize skin motion artifacts caused by segmental form change attributed to muscle contraction and marker oscillation.[5, 29] The participants walked barefoot at a self-selected comfortable speed along a 15-m walkway without assistive devices and took a rest before each trial until they had recovered from fatigue. Three sets of data with a whole gait cycle on the bilateral limbs were obtained. We collected the radiographic and gait data on the bilateral limbs of each patient for analysis. External knee adduction moments were calculated using the kinematic and kinetic data with a commercial software (Qualisys Track Manager 3D, Qualisys AB Inc., Gothenburg, Sweden) using a bottom-up dynamic-linked segment model.[23] The average data from three trials were obtained and used for the analysis of each limb.

Reliability of PKA measurement

We assessed the reliability of HKA and PKA measurements on full-length standing anteroposterior radiographs in the bipedal standing position in patients who underwent two sets of full-length standing anteroposterior radiographs before and after unicompartmental knee arthroplasty (UKA) within 4 weeks. The inclusion criteria for UKA were patients with an HKA of $<-5°$, those with a flexion contracture of $<-10°$, and those with a body mass index of <25 kg/m^2. Based on these criteria, there were minimal changes in the posture and leg alignment of the contralateral side before and after UKA. In total, 100 randomized radiograph images of 50 patients before and after UKA were assessed in two separate trials. Intrarater reliability, interrater reliability, and interradiograph reliability (the mean of the first radiograph in trials 1 and 2 vs. the mean of the second radiograph in trials 1 and 2) were calculated.

Statistical analysis

Statistical analysis was performed using JMP Pro version 14.0 (SAS Institute Inc.). A P value of <0.05 was considered statistically significant. The paired *t*-test was used to compare variables before and after HTO. A simple linear regression model was then used to evaluate the correlation between radiographic and background characteristics and KAM before and after HTO. The association between postoperative PKA and the postoperative first or second KAM peaks assessed via a multivariate regression analysis after adjusting for factors, including age, sex, gait speed, and radiographic OA severity, was evaluated. HKA was not significantly correlated with the postoperative first and second KAM peaks in the simple linear regression analysis. Hence, it was excluded from the multivariate analysis.

Relative reliability was estimated using an intraclass correlation coefficient (ICC).[27] The ICCs were classified as follows: >0.90, excellent reliability; between 0.75 and 0.9, good reliability; between 0.5 and 0.75, moderate reliability; and <0.5, poor reliability.[24]

With a power of 80% and $\alpha = 0.05$, the sample size was determined to detect the correlation coefficient ($r \geq 0.45$, corresponding to a moderate-to-large effect size) between PKA and KAM peaks.

Results

In total, 54 patients were analyzed. The mean HKA, PKA, gait speed, and first and second knee adduction moment peak significantly changed after HTO ($P < 0.01$ in all categories) (Table 2). The mean and standard deviation of postoperative HKA and PKA were 3.6° and 1.4° and 7.9° and 1.9°, respectively. The total and subscale scores of the KSS improved significantly after HTO (Table 2). Postoperative PKA was negatively correlated with HKA ($r = −0.42$, $P < 0.01$) (Figure 3A). HKA was weakly associated with the first ($r = −0.33$, $P < 0.01$) and second ($r = −0.27$, $P = 0.01$) KMA peaks. PKA was moderately correlated with the first ($r = 0.45$, $P < 0.01$) and second ($r = −0.45$, $P < 0.01$) KAM peaks before HTO. Postoperative HKA was not significantly associated with KAM peaks ($r = −0.26$, not significant in the first peak, $r = −0.20$, not significant in the second peak) after HTO (Figures 3B, 3C). However, postoperative PKA was moderately correlated with KAM peaks after HTO ($r = −0.51$, $P < 0.01$, in the first peak; $r = −0.56$, $P < 0.01$) (Figures 3D, 3E). Simple linear regression analysis showed a body weight × height (Bw × Ht) reduction in KAM peaks for every 1° reduction in postoperative PKA. Postoperative PKA showed variances of 25% and 31% in the postoperative first and second KAM peaks, respectively. After adjusting for age, sex, and baseline gait speed, multivariate linear regression analysis revealed that postoperative PKA was still associated with the first (β coefficient = 0.22, $P < 0.01$) and second ($\beta = 0.20$, $P < 0.01$) KAM peaks after HTO (Table 3).

Regarding PROMs, preoperative HKA, PKA, and KAM peaks were not correlated with the total preoperative KSS and each KSS subscale before HTO. Only postoperative PKA was significantly and negatively correlated with the postoperative KSS satisfaction subscale (r = −0.30, P = 0.03) (Table 4). Based on further analysis of the association between PKA and KSS symptoms and satisfaction subscales, the postoperative PKA was significantly correlated with satisfaction with pain at rest (Table 5).

Table 2. Gait speed, radiographic characteristics, and clinical outcomes[α]

	Patients with preoperative OA (n = 54)	Patients with postoperative OA (n = 54)	P value
HKA, degree	−4.0 ± 2.3	3.6 ±1.4	<0.001
PKA, degree	15.1 ± 2.2	7.9 ±1.9	<0.001
Gait speed, m/s	1.2 ± 0.2	1.3 ± 0.2	<0.001
Knee adduction moment			
First peak, %BW × Ht	2.5 ± 0.8	1.1 ± 0.8	<0.001
Second peak, %BW × Ht	2.4 ± 0.8	1.1 ± 0.7	<0.001
Knee Society Score			
Total (range: 0–200)	90.7 ± 21.2	132.9 ± 23.1	<0.001
Symptom (0–25)	11.9 ± 5.5	20.6 ± 4.3	<0.001
Satisfaction (0–40)	13.8 ± 5.0	25.6 ± 8.3	<0.001
Expectation (0–15)	12.7 ± 1.9	9.4 ± 2.6	<0.001
Functional activity (0–100)	52.3 ± 15.5	77.3 ± 14.6	<0.001

[α]Data were expressed as mean ± standard deviation unless otherwise stated.

HKA, hip–knee–ankle angle; PKA, pelvic–knee–ankle angle; BW, body weight; Ht, height

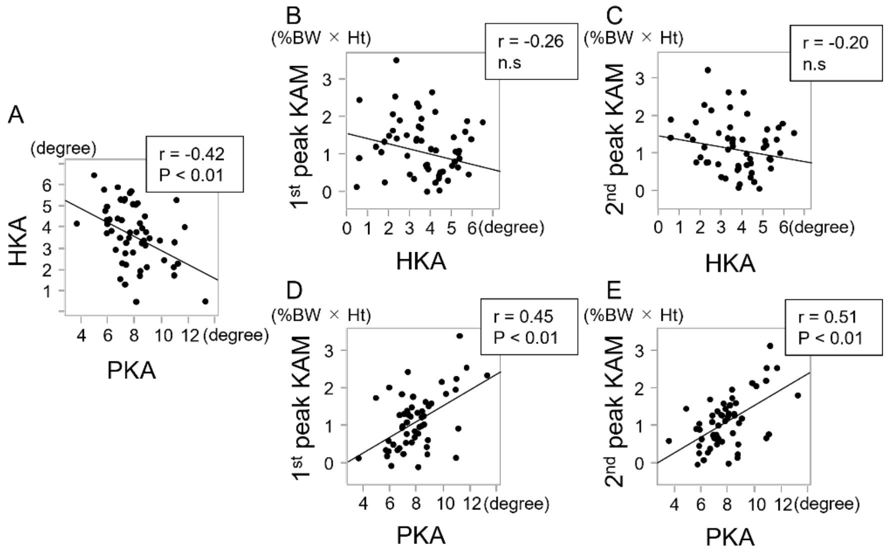

Figure 3. Single regression analysis of HKA, PKA, and KAM peaks after HTO. **A:** PKA and HKA. **B:** HKA and the first KAM peak. **C:** HKA and the second KAM peak. **D:** PKA and the first KAM peak (regression equation; −0.21 × PKA = −0.58). **E:** PKA and the second KAM peak (0.21 × PKA = −0.61). HKA, hip–knee–ankle angle; PKA, pelvis–knee–ankle angle; KAM, knee adduction moment; BW, body weight; Ht, height

Table 3. Multivariate linear regression analysis of knee adduction moment peaks after HTO

	First KAM peak				Second KAM peak			
			95% CI				95% CI	
	β coefficient	P value	Lower	Upper	β coefficient	P value	Lower	Upper
PKA	0.22	<0.01	0.11	0.32	0.20	<0.01	0.11	0.30
Age	−0.01	0.56	−0.26	0.32	−0.01	0.57	−0.04	0.02
Sex	−0.03	0.88	−0.43	0.36	0.10	0.67	−0.28	0.42
Gait speed	0.56	0.35	−0.63	1.75	0.10	0.78	−0.90	1.21
OA grade	−0.18	0.85	−0.26	0.32	−0.19	0.89	−0.23	0.27

PKA, pelvic–knee–ankle angle; KAM, knee adduction moment; n.s., not significant

Table 4. Correlation coefficient between postoperative HKA, PKA, and KAM peaks and patient-reported outcome measures after HTO

	HKA	PKA	First KAM	Second KAM

					peak		peak	
	r	P value	r	P value	r	P value	r	P value
Knee Society Score								
Total	0.06	0.65	−0.15	0.28	0.10	0.48	0.09	0.54
Symptom	0.05	0.71	−0.02	0.88	−0.04	0.76	0.12	0.37
Satisfaction	0.12	0.38	−0.30	0.03	−0.07	0.63	−0.12	0.39
Expectation	−0.02	0.89	0.07	0.60	0.19	0.16	0.07	0.61
Functional activity	0.02	0.88	−0.08	0.59	0.16	0.29	0.15	0.28

HKA, hip–knee–ankle angle; PKA, pelvic–knee–ankle angle; KAM, knee adduction moment; n.s., not significant

Table 5. Correlation coefficient between postoperative PKA and satisfaction subscale of the Knee Society Score

Knee Society Score	PKA	
Symptom subscale	r	p
1-Pain with level walking	0.06	0.67
2-Pain with stairs or inclines	−0.10	0.48
3-Does this knee feel “normal” to you?	−0.01	0.96
Satisfaction subscale score	r	p
1-Pain level while sitting	−0.31	0.02
2-Pain level while lying in bed	−0.27	0.05
3-Function while getting out of bed	−0.29	0.03
4-Function while performing household duties	−0.22	n. s.
5-Function while performing recreational activities	−0.23	n. s.

PKA, pelvic–knee–ankle angle; n.s., not significant

The intrarater, interrater, and interradiograph reliabilities of HKA (0.975, 0.948, and 0.922, respectively) and PKA (0.978, 0.952, and 0.933, respectively) on a full-length standing anteroposterior radiograph in the bipedal standing position were excellent.

Discussion

The most important findings of the current study are as follows: PKA was significantly correlated with KAM peaks in patients with varus knee OA after HTO. Further, only PKA was associated with the KSS satisfaction subscale.

The product of ground reaction force (GRF) and the lever arm is the moment. The KAM lever arm is an important variable in the examination of knee OA because the association between KAM peaks and the KAM lever arm was higher than that between KAM peaks and frontal plane GRF.[15] The simplified schema presenting the association between the KAM lever arm and PKA and KAM on a one-leg standing radiograph indicated that the KAM lever arm was influenced by leg alignment and pelvic width (Figures 1, 4A, and 4B). PKA could reflect leg alignment, pelvic width, and KAM lever arm. Meanwhile, HKA reflects leg alignment alone (Figure 1). After HTO, HKA was within the range aimed at by the surgeon. However, PKA varied based on pelvic width. Consequently, PKA was the main variable in the KAM lever arm (Figures 4A and 4B). Therefore, there might be a significant correlation between KAM peaks and PKA, but not with HKA, after HTO. A meta-analysis revealed that postoperative leg alignment was not associated with the change in KAM after HTO,[22] thereby supporting our results.

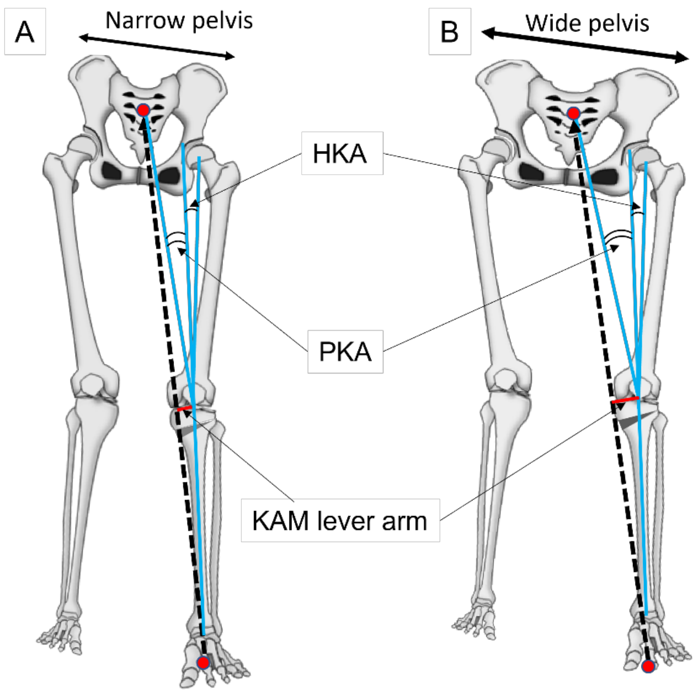

Figure 4. Association between KAM lever arm and PKA after HTO on a one-foot standing radiograph. **A.** Participant with a narrow pelvis. **B.** Participant with a wide pelvis. HKA, hip–knee–ankle angle; PKA, pelvis–knee–ankle angle; KAM, knee adduction moment; HTO, high tibial osteotomy.

Leg alignment is a factor affecting KAM in patients with and without knee OA.[3, 17] Previous studies reported a significant correlation between leg alignment and KAM before and after HTO.[7, 37] However, our study showed that HKA was correlated with KAM peaks before but not after HTO. The variance of the postoperative HKA was smaller (standard deviation: 1.4°) than that of previous studies (3°).[7, 37] KAM peaks were associated with postoperative HKA. However, there is no correlation between HKA and KAM peaks. This finding could be attributed to the small variance of postoperative HKA.

KAM is a surrogate of medial compartment loading.[4] However, a musculoskeletal simulation study reported that KAM reduction could not accurately explain the medial compression force.[9, 36] An *in vivo* study using force-measuring knee implants showed that KAM could not account for medial compartment loading at all.[38] In contrast, another study revealed a high correlation between KAM and mediolateral load distribution.[25] Therefore, the higher correlation between PKA and KAM must be interpreted with caution bearing in mind that PKA was associated with mediolateral load distribution but not with medial compartment loading.

Regression analysis showed a 0.21% Bw × Ht reduction in KAM peaks for every 1° reduction in postoperative PKA. Hence, a 2° difference in PKA, which is equivalent to one standard deviation (SD) of postoperative PKA (1.9°), corresponded to 0.42% Bw × Ht in KAM peaks. Considering that the mean change in KAM peaks before and after HTO was 1.4% Bw × Ht, one SD difference in PKA accounted for approximately 30% of the change in KAM peaks. Thus, PKA is an important variable in postoperative mediolateral loading distribution.

A previous study on patients with a force-measuring knee implant reported significant correlations between the mediolateral load distribution and the external frontal plane lever arm (EFL), defined as the perpendicular line from the center of the knee joint to the line connecting the center of the ankle joint and the symphysis pubis.[6] These results supported the notion that the correlation between PKA and KAM peaks was higher than that between PKA and HKA before and after HTO because the concept of EFL when reflecting pelvic width is similar to PKA.

HTO can realign the knee joint and change the mediolateral load distribution across the knee joint.[1, 3, 9] Hence, the load distribution is a key factor for a successful HTO. However, most surgeons could not identify the load distribution because only a few institutions could perform this analysis using a three-dimensional gait analysis system equipped with force plates and motion sensors. While PKA was significantly correlated with KAM after HTO, no association was observed between HKA and KAM. Hence, PKA, but not HKA, reflected the load distribution. Using PKA in HTO planning or evaluation, surgeons could perform HTO or evaluate postoperative outcomes with consideration of mediolateral load distribution. This could eventually lead to improvements in HTO outcomes.

Pain during rest and activities is the primary complaint of patients with unicompartmental femorotibial OA. In this study, postoperative PKA was associated with PROMs. However, neither postoperative KAM peaks nor HKA was correlated with satisfaction based on the KSS subscale. On further analysis, PKA was negatively associated with satisfaction with pain at rest, confirming the correlation of postoperative PKA with pain at rest. Pain during activities was evaluated using the KSS symptom subscale (0–25 points), and at a score of 24.9, +1 SD of the postoperative symptom subscale was assigned, thereby demonstrating a ceiling effect as the distribution of the scores for the postoperative symptom subscale skewed toward high scores. This made it difficult to determine the relationship between pain in dynamic and PKA, and thus, the correlation between PKA and pain in a dynamic setting was not validated in this analysis.

The current study had several limitations. First, PKA was a two-dimensional parameter at rest. It could not reflect dynamic factors, such as postural change during walking. However, the correlation between PKA and KAM peaks was higher than that between PKA and HKA. Moreover, it was an easy-to-use and convenient parameter for predicting outliers in KAM peaks with average leg alignment after HTO. Second, when standing on one leg, the center of mass is anterior to the second sacral vertebra.[32] As a result, the correlation between PKA and KAM differs between the one-leg standing radiograph and the bipedal standing radiograph. However, one-leg standing radiographs can be difficult to obtain in elderly patients due to knee pain and/or quadriceps weakness.[16] Therefore, a full-length standing anteroposterior radiograph in the bipedal standing position was performed to assess PKA and HKA while prioritizing radiograph reproducibility in this study. Third, PKA could not reflect the influence of foot alignment on KAM on full-length standing anteroposterior radiographs of the lower limb.[8, 17, 20] A hip-to-calcaneus radiograph was useful for evaluating whole-leg and foot alignment.[13] Further studies using hip–knee–calcaneus radiographs should investigate the association between KAM and lower body alignment, including the pelvis, hip, knee, ankle, and foot. Given the above limitations, it should be kept in mind that PKA does not explain all the variation in KAM. Fourth, this study was retrospective in nature. and thus, had a low level of evidence, unlike prospective studies. However, this study is the first to report that the correlation between PKA and KAM was higher than that between PKA and HKA. Hence, our findings could serve as a reference for future prospective studies using PKA in planning knee osteotomy.

In conclusion, PKA was significantly correlated with KAM peaks and patient-reported outcomes in patients with varus knee OA before and after HTO. However, HKA was not correlated with KAM peaks after

HTO. Hence, more attention should be paid to the distribution of mediolateral loading after HTO, and PKA could be a potential radiographic parameter in HTO planning with consideration of postoperative mediolateral load distribution.

References

1. Agneskirchner JD, Hurschler C, Wrann CD, Lobenhoffer P. The effects of valgus medial opening wedge high tibial osteotomy on articular cartilage pressure of the knee: a biomechanical study. *Arthroscopy.* 2007;23(8):852-861.
2. Akizuki S, Shibakawa A, Takizawa T, Yamazaki I, Horiuchi H. The long-term outcome of high tibial osteotomy: a ten- to 20-year follow-up. *J Bone Joint Surg Br.* 2008;90(5):592-596.
3. Andrews M, Noyes FR, Hewett TE, Andriacchi TP. Lower limb alignment and foot angle are related to stance phase knee adduction in normal subjects: a critical analysis of the reliability of gait analysis data. *J Orthop Res.* 1996;14(2):289-295.
4. Andriacchi TP. Dynamics of knee malalignment. *Orthop Clin North Am.* 1994;25(3):395-403.
5. Andriacchi TP, Alexander EJ, Toney MK, Dyrby C, Sum J. A point cluster method for in vivo motion analysis: applied to a study of knee kinematics. *J Biomech Eng.* 1998;120(6):743-749.
6. Biehl M, Damm P, Trepczynski A, Preiss S, Salzmann GM. Towards planning of osteotomy around the knee with quantitative inclusion of the adduction moment: a biomechanical approach. *J Exp Orthop.* 2021;8(1):39.
7. Birmingham TB, Giffin JR, Chesworth BM, et al. Medial opening wedge high tibial osteotomy: A prospective cohort study of gait, radiographic, and patient-reported outcomes. *Arthritis Rheum.* 2009;61:648-657.
8. Cui WL, Wang CJ, Chen WY, et al. Effects of toe-out and toe-in gaits on lower-extremity kinematics dynamics, and electromyography. *Appl Sci (Basel).* 2019;9(23).
9. De Pieri E, Nuesch C, Pagenstert G, Viehweger E, Egloff C, Mundermann A. High tibial osteotomy effectively redistributes compressive knee loads during walking. *J Orthop Res.* 2022.
10. Deie M, Hoso T, Shimada N, et al. Differences between opening versus closing high tibial osteotomy on clinical outcomes and gait analysis. *Knee.* 2014;21(6):1046-1051.
11. Doherty M, Watt I, Dieppe P. Influence of primary generalised osteoarthritis on development of secondary osteoarthritis. *Lancet.* 1983;2(8340):8-11.
12. Goutallier D, Hernigou P, Medevielle D, Debeyre J. [Outcome at more than 10 years of 93 tibial osteotomies for internal arthritis in genu varum (or the predominant influence of the frontal angular correction)]. *Rev Chir Orthop Reparatrice Appar Mot.* 1986;72(2):101-113.
13. Haraguchi N, Ota K, Tsunoda N, Seike K, Kanetake Y, Tsutaya A. Weight-bearing-line analysis in

supramalleolar osteotomy for varus-type osteoarthritis of the ankle. *J Bone Joint Surg Am.* 2015;97(4):333-339.

14. Hunt MA, Birmingham TB, Bryant D, et al. Lateral trunk lean explains variation in dynamic knee joint load in patients with medial compartment knee osteoarthritis. *Osteoarthr Cartil.* 2008;16(5):591-599.

15. Hunt MA, Birmingham TB, Giffin JR, Jenkyn TR. Associations among knee adduction moment, frontal plane ground reaction force, and lever arm during walking in patients with knee osteoarthritis. *J Biomech.* 2006;39(12):2213-2220.

16. Hunt MA, McManus FJ, Hinman RS, Bennell KL. Predictors of single-leg standing balance in individuals with medial knee osteoarthritis. *Arthritis Care Res (Hoboken).* 2010;62(4):496-500.

17. Hurwitz DE, Ryals AB, Case JP, Block JA, Andriacchi TP. The knee adduction moment during gait in subjects with knee osteoarthritis is more closely correlated with static alignment than radiographic disease severity, toe out angle and pain. *J Orthop Res.* 2002;20(1):101-107.

18. Insall JN, Joseph DM, Msika C. High tibial osteotomy for varus gonarthrosis. A long-term follow-up study. *J Bone Joint Surg Am.* 1984;66(7):1040-1048.

19. Iwasaki K, Kondo E, Matsubara S, et al. Effect of high tibial osteotomy on the distribution of subchondral bone density across the proximal tibial articular surface of the knee with medial compartment osteoarthritis. *Am J Sports Med.* 2021;49(6):1561-1569.

20. Jenkyn TR, Hunt MA, Jones IC, Giffin JR, Birmingham TB. Toe-out gait in patients with knee osteoarthritis partially transforms external knee adduction moment into flexion moment during early stance phase of gait: a tri-planar kinetic mechanism. *J Biomech.* 2008;41(2):276-283.

21. Kellgren JH, Lawrence JS. Radiological assessment of osteo-arthrosis. *Ann Rheum Dis.* 1957;16(4):494-502.

22. Kim JH, Kim HJ, Celik H, Kim JH, Lee DH. Change in adduction moment following medial open wedge high tibial osteotomy: a meta-analysis. *BMC Musculoskelet Disord.* 2019;20(1):102.

23. Kingma I, deLooze MP, Toussaint HM, Klijnsma HG, Bruijnen TBM. Validation of a full body 3-D dynamic linked segment model. *Hum Mov Sci.* 1996;15(6):833-860.

24. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med.* 2016;15(2):155-163.

25. Kutzner I, Trepczynski A, Heller MO, Bergmann G. Knee adduction moment and medial contact force--facts about their correlation during gait. *PLoS ONE.* 2013;8(12):e81036.

26. Leitch KM, Birmingham TB, Dunning CE, Giffin JR. Medial opening wedge high tibial osteotomy alters knee moments in multiple planes during walking and stair ascent. *Gait Posture.* 2015;42(2):165-171.

27. Mau-Moeller A, Gube M, Felser S, et al. Intrarater reliability of muscle strength and hamstring to quadriceps strength imbalance ratios during concentric, isometric, and eccentric maximal voluntary contractions using the isoforce dynamometer. *Clin J Sport Med.* 2019;29(1):69-77.

28. Miniaci A, Ballmer FT, Ballmer PM, Jakob RP. Proximal tibial osteotomy. A new fixation device. *Clin Orthop Relat Res.* 1989;246:250-259.

29. Miura K, Ohkoshi Y, Ino T, et al. Kinematics and center of axial rotation during walking after medial pivot type total knee arthroplasty. *J Exp Orthop.* 2020;7(1):72.

30. Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shimada S. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. *Ann Rheum Dis.* 2002;61(7):617-622.

31. Mundermann A, Asay JL, Mundermann L, Andriacchi TP. Implications of increased medio-lateral trunk sway for ambulatory mechanics. *J Biomech.* 2008;41(1):165-170.

32. Peizer E. Human locomotion. *Bull Prosthet Res.* 1969;Fall:48-105.

33. Prodromos CC, Andriacchi TP, Galante JO. A relationship between gait and clinical changes following high tibial osteotomy. *J Bone Joint Surg Am.* 1985;67(8):1188-1194.

34. Scuderi GR, Bourne RB, Noble PC, Benjamin JB, Lonner JH, Scott WN. The new Knee Society Knee Scoring System. *Clin Orthop Relat Res.* 2012;470(1):3-19.

35. Sharma L, Hurwitz DE, Thonar EJ, et al. Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. *Arthritis Rheum.* 1998;41(7):1233-1240.

36. Shelburne KB, Torry MR, Steadman JR, Pandy MG. Effects of foot orthoses and valgus bracing on the knee adduction moment and medial joint load during gait. *Clin Biomech (Bristol, Avon).* 2008;23(6):814-821.

37. Wada M, Imura S, Nagatani K, Baba H, Shimada S, Sasaki S. Relationship between gait and clinical results after high tibial osteotomy. *Clin Orthop Relat Res.* 1998;354:180-188.

38. Walter JP, D'Lima DD, Colwell CW, Jr., Fregly BJ. Decreased knee adduction moment does not guarantee decreased medial contact force during gait. *J Orthop Res.* 2010;28(10):1348-1354.