scientific reports

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Correction to at least neutral alignment during high tibial osteotomy is sufficient in reducing the knee adduction moment

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High tibial osteotomy (HTO) for varus knee osteoarthritis traditionally aims to overcorrect the mechanical tibiofemoral angle (mTFA) to become valgus. However, valgus overcorrection in HTO increases problems such as knee joint line abnormality, hinge fracture, and patellar height change. Thus, there is a trend to avoid overcorrection, but biomechanical basis for abandoning the overcorrection is lacking. From a dynamic perspective, medial-to-lateral knee joint load distribution during gait can be reflected by knee adduction moment (KAM), and the main purpose of HTO is to reduce the KAM increased during gait due to varus alignment. We tried to reveal the association between the KAM obtained from three-dimensional gait analysis and various static alignment parameters, including mTFA, measured from the standing whole limb anteroposterior radiograph and through this, to suggest a dynamically optimal target for HTO. When grouped according to the alignment by the interval of 1°, lower extremities with 3° to 8° of varus had greater KAM values than those with 0° to 5° of valgus. However, within groups of 0° to 5° of valgus, there were no significant differences. Therefore, the varus must be corrected to at least neutral alignment during HTO, but valgus overcorrection does not further reduce the KAM.

According to a systematic analysis, the global prevalence of knee osteoarthritis (OA) is 16.0% and its incidence is 203 per 10,000 person-years[1]. OA of the knee refers to the degenerative joint disease of the medial and lateral tibiofemoral and the patellofemoral compartments. It more frequently involves the medial tibiofemoral compartment than the others. The treatment of medial knee OA consists of operative managements such as alignment-correcting osteotomies and arthroplasty as well as conservative managements including laterally wedged shoes or insoles, toe-out gait, and valgus unloader knee braces[2]. Before treatment decisions, thorough radiographic assessments are necessary. Although expensive and time-consuming, dynamic study such as gait analysis is additionally performed in some orthopedic centers to provide biomechanical perspective to the patient's knee. Among several variables measured during gait analysis, knee adduction moment (KAM) has widely received attention. The KAM is defined as the ground reaction force multiplied by its lever arm which is the perpendicular distance from the ground reaction force vector to the knee joint center[2,3]. The KAM acts to adduct the knee into a varus position[4]. It serves as a surrogate marker for the contact force and loading of the medial compartment[5–7] and OA progression[8]. Moreover, several studies have reported that the KAM increases with the severity of knee OA[4,9].

In a previous study from our group, the relationships between the KAM variables, namely, the KAM-time integral (KAM impulse) and the maximum KAM at stance phase measured with the three-dimensional (3D) gait analysis and the radiographic alignment parameters were analyzed. Both mechanical tibiofemoral angle (mTFA) and ankle joint line orientation (AJLO) relative to the ground independently explained the KAM. However, the study included only OA patients with varus knee alignment[10]. The relationship, therefore, could not be extrapolated to a general population or those with valgus knee alignment.

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Because the medial compartment OA is known to aggravate with more varus alignment[11], high tibial osteotomy (HTO) could be performed preferably in patients younger than 65 years old in order to unload the medial compartment. Miniaci's and Dugdale's methods have been traditionally used to preoperatively estimate the amount of correction needed in the HTO operation[12]. They usually locate the weight-bearing line at 62.5% of the tibial width, as measured from the medial to lateral edge of the tibial plateau, thus correcting the pre-existing varus alignment to 3° to 5° of mechanical valgus[13]. However, these preoperative surgical plannings were derived only from the radiological perspective based on static images. Although Yasuda et al. reported favorable long-term results in HTO with corrected mTFA of 12° to 16°[14], valgus overcorrection might lead to problems such as knee joint line abnormality[15], lateral hinge fracture[16], leg length difference[17], patellar height change[18,19], patellar maltracking[19,20], and decreased functional outcome[15,20]. Because of these problems, there is a trend to avoid overcorrection during HTO[21–24], but there is a lack of dynamic perspective for abandoning the conventional overcorrection.

Equipped with the 3D gait analysis, the planning of HTO can also be approached from the biomechanical viewpoint. The KAM is reported to decrease following HTO[25,26] and some researchers emphasized that the preoperative KAM could influence the outcome of the operation[25] while others highlighted the effect of the postoperative alignment on the KAM[26]. Analysis of the KAM derived from subjects with different limb alignment would provide more insight to the amount of correction needed to achieve significant reduction in the KAM following the HTO.

In this study, our purpose was to analyze factors associated with the KAM-time integral and the maximum KAM values by reviewing the 3D gait analysis and radiographic alignment parameters of 500 randomly-selected volunteers from an urban area in Korea. Moreover, by categorizing each lower extremity according to its alignment, we aimed to compare the KAM-time integral and the maximum KAM according to the alignment groups. We intended to extend the understanding of the radiographic alignment parameters associated with the KAM and the relationship of the KAM with the degree of the lower limb alignment, providing background for the amount of alignment correction needed in the HTO.

Results

Population characteristics

The mean positive KAM-time integral, negative KAM-time integral, and maximum KAM were 0.13 ± 0.05 Nms/kg, 0.0039 ± 0.010 Nms/kg, and 0.36 ± 0.12 Nm/kg, respectively. The characteristics of the study population are summarized in Table 1. Differences of variables according to sex are provided in Supplementary Table S1.

Correlation study between the KAM and other variables

The results of the correlation analyses between the KAM and other variables are shown in Table 2. mTFA had the strongest correlation with both the positive KAM-time integral and the maximum KAM ($r = 0.376$ and

Data summary of lower extremities	
No	937
Age (years)	36.8 (SD, ± 16.5)
Sex (men:women)	471:466 (50.3%:49.7%)
Side (right:left)	470:467 (49.8%:50.2%)
Height (cm)	165.8 (SD, ± 8.9)
Weight (kg)	64.0 (SD, ± 12.8)
BMI (kg/m^2)	23.1 (SD, ± 3.4)
Kinetic data	
Maximum KAM (Nm/kg)	0.36 (SD, ± 0.12)
Positive KAM-time integral (Nms/kg)	0.13 (SD, ± 0.05)
Negative KAM-time integral (Nms/kg)	0.0039 (SD, ± 0.010)
Radiographic measurements	
Medial K-L grade (0/I/II/III/IV)	780/139/17/1/0 (83.2%/14.8%/1.8%/0.1%/0%)
Lateral K-L grade (0/I/II/III/IV)	856/77/4/0/0 (91.4%/8.2%/0.4%/0%/0%)
mTFA (°)	1.16 (SD, ± 2.50)
MPTA (°)	86.2 (SD, ± 2.19)
LDFA (°)	86.8 (SD, ± 2.05)
KJLO (°)	1.46 (SD, ± 2.21)
AJLO (°)	-2.44 (SD, ± 3.96)
JLCA (°)	0.53 (SD, ± 1.40)
Tibiofemoral translation	3.24 (SD, ± 2.50)

Table 1. Characteristics of the lower extremities included in the analysis. *SD* standard deviation, *BMI* body mass index, *KAM* knee adduction moment, *K-L* Kellgren-Lawrence, *mTFA* mechanical tibiofemoral angle, *MPTA* medial proximal tibial angle, *LDFA* lateral distal femoral angle, *KJLO* knee joint line orientation, *AJLO* ankle joint line orientation, *JLCA* joint line convergence angle.

0.383, respectively) followed by AJLO (r = -0.258 and -0.269). The negative KAM-time integral had negative and positive correlation with mTFA (r = -0.095) and MPTA (r = 0.076), respectively.

Multiple regression analysis for the KAM variables

Sex, medial K-L grade, mTFA, MPTA, and AJLO comprised the final model for the positive KAM-time integral while mTFA and AJLO were included in the model for the maximum KAM. Both mTFA and AJLO independently explained the variance of the positive KAM-time integral the most while mTFA was the main explanatory parameter of the maximum KAM. The model for negative KAM-time integral included only mTFA (Table 3).

Positive KAM-time integral = 0.295 + (-0.009) x Sex + 0.012 × medial K-L grade + 0.006 × mTFA + (-0.002) x MPTA + (-0.003) x AJLO (R^2 = 0.1917, adjusted R^2 = 0.1874).

(1 and 2 for male and female, respectively).

Maximum KAM = 0.330 + 0.017 × mTFA + (-0.006) x AJLO (R^2 = 0.1843, adjusted R^2 = 0.1825).

Negative KAM-time integral = 0.0044 + (-0.0004) x mTFA (R^2 = 0.0091, adjusted R^2 = 0.0081).

Analysis according to mTFA by the interval of 1°

There was a tendency that the positive KAM-time integral and the maximum KAM increased as mTFA increased (P < 0.001, Table 4). The post-hoc analysis of ANOVA of the positive KAM-time integral and the maximum KAM of alignment groups are shown in Table 5. The positive KAM-time integral values of lower extremities of varus alignment groups with 3° ≤ mTFA < 8° were significantly greater than those of neutral or valgus alignment groups with -5° ≤ mTFA < 0°. Similar relationship was observed in the maximum KAM among those with 3° ≤ mTFA < 8° and -5° ≤ mTFA < 0°, except that the P-value of the post-hoc analysis of the maximum KAM between the alignment groups -1° ≤ mTFA < 0° and 5° ≤ mTFA < 6° was slightly greater than 0.05 (P = 0.088). Although the positive KAM-time integral and the maximum KAM showed decreasing tendency in alignment groups of -5° ≤ mTFA < 0°, there was no significant difference of the positive KAM-time integral and the maximum KAM within these groups (Table 5). There was no increasing tendency of the negative KAM as the amount of valgus increased (Table 4). Every alignment group with 3° to 7° of mTFA included more male than female extremities whereas female lower extremities were more prevalent in alignment groups with -4° to 0° of mTFA (P < 0.001).

Interobserver reliability test

Table 6 shows ICCs for each variable. Every coefficient value was greater than 0.8, implying good to excellent interobserver reliability[27].

Discussion

In the analysis of 937 lower extremities of randomly-selected individuals of Seongnam, Korea, the positive KAM-time integral could be independently explained by sex, medial K-L grade, mTFA, MPTA, and AJLO. The variance in maximum KAM were independently explained by mTFA and AJLO. There was a tendency of increasing positive KAM-time integral and maximum KAM as the amount of varus alignment increased. When the lower extremities were categorized into alignment groups of 1° interval, lower extremities with 3° to 8° of varus had greater values of the positive KAM-time integral and the maximum KAM than those with 0° to 5° of valgus. However, within the alignment groups of 0° to 5° of valgus, there was no significant difference in the positive KAM-time integral and the maximum KAM.

In our study population, older participants and more male than female individuals had more varus limb alignment (Supplementary Table S1). In a landmark study conducted by Bellemans et al., the constitutional varus group were composed of older participants and its proportion of K-L grade 2 was higher than that of either the neutral or valgus alignment groups[28]. Colyn et al. reported increase in varus alignment during the arthritic progression when comparing consecutive full-length X-rays of the same patients over mean 2 years[29]. Despite the cross-sectional nature of our study, lower extremities with varus alignment belonged more to the older individuals, which was in agreement with the progression of varus alignment as one ages. Interestingly, significantly more male lower extremities belonged to the varus alignment group. Male lower extremities had greater mean varus alignment (1.70° vs. 0.61°) and had lower mean MPTA (85.8° vs. 86.6°) than those of female while there was no significant difference in LDFA between the sexes. This may be the reason why male population had positive correlation with the positive KAM-time integral and the maximum KAM. Moreover, the final model for the positive KAM-time integral in the multiple regression analysis also included male sex as an independent explanatory variable though its net contribution was less than 1%. The trends that there are more males than females with varus limb alignment due to the smaller MPTA in males have been reported in a healthy Korean population[30] and other ethnic groups as well[28,31]. Hueter-Volkmann law partly explains this phenomenon[30,32] because men are tended to be more physically active than women in younger populations.

mTFA and AJLO had the strongest correlation with the positive KAM-time integral and the maximum KAM in the correlation study. The following multiple regression analyses revealed the quantitative relationship between the positive KAM-time integral and sex, medial K-L grade, mTFA, MPTA, and AJLO. Although they only explained less than 1% of the variance of the positive KAM-time integral when other variables were included, grade of OA in the medial compartment and tibia vara increased the positive KAM-time integral but not the maximum KAM. The KAM-time integral was noted to be more sensitive at distinguishing between K-L grades than the maximum KAM[9]. However, when backward eliminations were performed from the final model for the positive KAM-time integral, mTFA and AJLO were the main explanatory variables. This relationship between the KAM variables and mTFA and AJLO was demonstrated in the previous study of our group which only included patients with varus knee OA[10]. Our study extends this relationship to a general population including participants with valgus limb alignments. The correlation between the maximum KAM and the ankle inversion moment was reported[33,34]. The varus position of the ankle in the stance phase of the gait cycle produces

	Age	Sex Male: 1 Female: 2	Height	Weight	BMI	Positive KAM-time integral	Negative KAM-time integral	Maximum KAM	K-L grade (medial)	K-L grade (lateral)	mTFA	MPTA	LDFA	KJLO	AJLO	JLCA	Tibiofemoral translation
Positive KAM-time integral	0.145 (<0.001)	-0.125 (<0.001)	0.054 (0.097)	0.015 (0.645)	-0.004 (0.907)		-0.374 (<0.001)	0.924 (<0.001)	0.140 (<0.001)	0.088 (0.007)	0.376 (<0.001)	-0.240 (<0.001)	0.184 (<0.001)	0.036 (0.266)	-0.258 (<0.001)	-0.011 (0.729)	0.036 (0.274)
Negative KAM-time integral	-0.064 (0.050)	0.064 (0.050)	-0.014 (0.669)	-0.038 (0.251)	-0.052 (0.113)	-0.374 (<0.001)		-0.442 (<0.001)	-0.026 (0.435)	-0.048 (0.140)	-0.095 (0.003)	0.076 (0.021)	-0.060 (0.065)	-0.037 (0.254)	0.034 (0.301)	0.037 (0.253)	-0.059 (0.069)
Maximum KAM	0.103 (0.002)	-0.087 (0.008)	0.016 (0.628)	-0.019 (0.559)	-0.021 (0.515)	0.924 (<0.001)	-0.442 (<0.001)		0.106 (0.001)	0.056 (0.085)	0.383 (<0.001)	-0.250 (<0.001)	0.199 (<0.001)	0.026 (0.434)	-0.269 (<0.001)	-0.031 (0.336)	0.025 (0.451)

Table 2. Correlation analyses between the KAM-time integral and the maximum KAM and the anthropometric and radiographic variables. P-values are written in parentheses. *BMI* body mass index, *KAM* knee adduction moment, *K-L* Kellgren-Lawrence, *mTFA* mechanical tibiofemoral angle, *MPTA* medial proximal tibial angle, *LDFA* lateral distal femoral angle, *KJLO* knee joint line orientation, *AJLO* ankle joint line orientation, *JLCA* joint line convergence angle.

	Non-standardized		Standardized β	t	P-value	VIF
	β	Standard error				
(a)						
Sex Male: 1 Female: 2	-0.009	0.003	-0.087	-2.806	0.005	1.097
Medial K-L grade	0.012	0.004	0.096	3.123	0.002	1.084
mTFA	0.006	0.001	0.256	6.736	<0.001	1.663
MPTA	-0.002	0.001	-0.076	-2.099	0.036	1.498
AJLO	-0.003	0.000	-0.206	-6.736	<0.001	1.077
Intercept	0.295	0.078		3.794	<0.001	
(b)						
mTFA	0.017	0.001	0.342	11.329	<0.001	1.686
AJLO	-0.006	0.001	-0.198	-6.558	<0.001	1.064
Intercept	0.330	0.004		75.473	<0.001	
(c)						
mTFA	-0.0004	0.0001	-0.0955	-2.9330	0.0034	
Intercept	0.0044	0.0004		11.9840	<0.001	
(d)						
Adjusted R^2 for Positive KAM-time integral						
0.1874	Sex + medial K-L grade + mTFA + MPTA + AJLO					
0.1814	Medial K-L grade + mTFA + MPTA + AJLO					
0.1844	Sex + medial K-L grade + mTFA + AJLO					
0.1797	Sex + mTFA + + MPTA + AJLO					
0.1487	Sex + medial K-L grade + mTFA + MPTA					
0.1487	Sex + medial K-L grade + MPTA + AJLO					
Adjusted R^2 for Maximum KAM						
0.1825	mTFA + AJLO					
0.1458	mTFA					
0.0712	AJLO					

Table 3. Factors associated with the KAM variables in the multiple regression analysis. (a) Positive KAM-time integral, $R^2 = 0.1917$, adjusted $R^2 = 0.1874$. (b) maximum KAM, $R^2 = 0.1843$, adjusted $R^2 = 0.1825$. (c) Negative KAM-time integral, $R^2 = 0.0091$, adjusted $R^2 = 0.0081$. (d) adjusted R^2 for predictors of the positive KAM-time integral and maximum KAM. *VIF* variance inflation factor, *K-L* Kellgren-Lawrence, *mTFA* mechanical tibiofemoral angle, *MPTA* medial proximal tibial angle, *KJLO* knee joint line orientation, *AJLO* ankle joint line orientation.

adduction force to the knee joint probably by laterally shifting the center of the knee joint. This association provides biomechanical grounds for laterally wedged shoes or insoles as means of conservative management for the medial knee OA. Upon performing HTO, preoperative lateral inclination of the ankle joint is reported to change into a less laterally-inclined or neutral orientation postoperatively[35–37]. Therefore, HTO could have a double positive effect in reducing the KAM by decreasing mTFA and increasing AJLO. The magnitude of R^2 values is less than 20% in all of our multiple regression analyses. There may be other factors not considered in our study such as foot progression angle, and walking speed[34,38,39]. Since mechanical axis was reported to account for about 50% of the variation in the peak KAM in patients with OA[38], R^2 values seem too small even if we had considered other factors which are known to influence the KAM. This difference might be attributed to the fact that randomly-selected volunteers instead of known OA patients were enrolled in our study. The correlation coefficient between alignment and the maximum KAM was 0.383 in our study, smaller than those calculated from studies with knee OA patients (0.751[38], 0.59[26], and 0.543[10]). Coronal tibiofemoral translation did not have significant correlation with the positive KAM-time integral and the maximum KAM in our study probably due to relatively competent collateral ligament status in general but not osteoarthritic population setting.

The positive KAM-time integral and the maximum KAM of lower extremities with 3° to 8° of varus were greater than those of 0° to 5° of valgus alignment, respectively. It can be inferred that in order to reduce the KAM-time integral and the maximum KAM significantly, the amount of correction should at least reach neutral alignment when performing HTO. Wada et al., comparing the low and high adduction moment group that underwent HTO, advocated valgus overcorrection to prevent varus recurrence[26]. In a 10- to 15-year follow-up study, Yasuda et al. addressed that mTFA of 12° to 16° should be attained to ensure good long-term outcome[14]. However, there was no significant difference of the positive KAM-time integral and the maximum KAM within the alignment groups of 0° to 5° of valgus in our study, implying that valgus overcorrection seems to offer no additional benefit in reducing the KAM values. According to a meta-analysis investigating the amount of knee adduction moment loss after medial open wedge HTO, KAM after the operation decreased to 60% of the preoperative level. The

	No	Male No	Female No	Age (years)	Positive KAM-time integral (Nms/kg)	Negative KAM-time integral (Nms/kg)	Maximum KAM (Nm/kg)
mTFA ≥ 10	1 (0.1%)	0	1	59.0	0.266	0.000	0.656
9 ≤ mTFA < 10	1 (0.1%)	1	0	61.0	0.194	0.000	0.492
8 ≤ mTFA < 9	1 (0.1%)	1	0	61.0	0.254	0.000	0.658
7 ≤ mTFA < 8	9 (1.0%)	3	6	49.6	0.193 (SD, ± 0.071)	0.001 (SD, ± 0.002)	0.478 (SD, ± 0.145)
6 ≤ mTFA < 7	18 (1.9%)	14	4	48.7	0.181 (SD, ± 0.062)	0.002 (SD, ± 0.003)	0.479 (SD, ± 0.139)
5 ≤ mTFA < 6	15 (1.6%)	11	4	43.7	0.174 (SD, ± 0.062)	0.007 (SD, ± 0.019)	0.441 (SD, ± 0.115)
4 ≤ mTFA < 5	73 (7.8%)	50	23	42.2	0.164 (SD, ± 0.051)	0.003 (SD, ± 0.006)	0.429 (SD, ± 0.101)
3 ≤ mTFA < 4	103 (11.0%)	65	38	39.8	0.153 (SD, ± 0.054)	0.003 (SD, ± 0.006)	0.407 (SD, ± 0.120)
2 ≤ mTFA < 3	131 (14.0%)	67	64	36.7	0.142 (SD, ± 0.055)	0.003 (SD, ± 0.007)	0.383 (SD, ± 0.115)
1 ≤ mTFA < 2	138 (14.7%)	84	54	39.9	0.136 (SD, ± 0.051)	0.003 (SD, ± 0.013)	0.373 (SD, ± 0.121)
0 ≤ mTFA < 1	141 (15.0%)	67	74	36.0	0.128 (SD, ± 0.047)	0.005 (SD, ± 0.011)	0.350 (SD, ± 0.103)
-1 ≤ mTFA < 0	121 (12.9%)	50	71	33.2	0.119 (SD, ± 0.043)	0.005 (SD, ± 0.012)	0.334 (SD, ± 0.105)
-2 ≤ mTFA < -1	86 (9.2%)	29	57	32.8	0.108 (SD, ± 0.042)	0.004 (SD, ± 0.009)	0.308 (SD, ± 0.099)
-3 ≤ mTFA < -2	59 (6.3%)	12	47	30.4	0.104 (SD, ± 0.045)	0.006 (SD, ± 0.014)	0.293 (SD, ± 0.121)
-4 ≤ mTFA < -3	22 (2.3%)	8	14	26.8	0.097 (SD, ± 0.037)	0.007 (SD, ± 0.010)	0.289 (SD, ± 0.089)
-5 ≤ mTFA < -4	13 (1.4%)	7	6	29.8	0.096 (SD, ± 0.074)	0.006 (SD, ± 0.011)	0.265 (SD, ± 0.121)
-6 ≤ mTFA < -5	2 (0.2%)	1	2	41.0	0.156 (SD, ± 0.066)	0.001 (SD, ± 0.001)	0.397 (SD, ± 0.146)
-7 ≤ mTFA < -6	1 (0.1%)	1	1	23.0	0.328	0.000	0.600
-8 ≤ mTFA < -7	2 (0.2%)	1	1	23.5	0.078 (SD, ± 0.046)	0.004 (SD, ± 0.005)	0.221 (SD, ± 0.100)
Total	937	471	466				

Table 4. The positive and negative KAM-time integral, and the maximum KAM values according to the alignment groups of one-degree interval. *SD* standard deviation, *KAM* knee adduction moment, *mTFA* mechanical tibiofemoral angle.

authors also reported that there was no significant association between alignment correction amount and difference in the KAM before and after the operation[40]. Our findings support their conclusion though our study could only compare the KAM values of lower extremities cross-sectionally. While the alignment group of 6° to 7° of valgus showed significant difference in the positive KAM-time integral with alignment groups of 0° to 5° and 7° to 8° of valgus, there was only one limb with the 6° to 7° valgus alignment, which could be interpreted as bias due to small sample size in the group. In conjunction with recent trend to avoid valgus overcorrection in HTO[21,23,24] which might cause problems such as knee joint line abnormality[15], lateral hinge fracture[16], and patellar maltracking[19,20], our study advocates correction to at least neutral alignment when performing HTO but excessive valgus correction provides no significant reduction in the KAM values. Further studies are needed to validate whether this amount of reduction in the KAM values has clinically significant effects. Moreover, we look forward to clinical studies comparing the postoperative KAM and functional outcomes of correction to neutral and valgus-corrected alignments after HTO.

Peak knee joint moments are reported to be strongly correlated with both peak medial and lateral knee joint contact forces in knees with valgus malalignment[5]. The negative KAM-time integral among the alignment groups did not show increasing trend as the amount of valgus increased. This might be due to the small absolute value of the negative KAM-time integral and to the relatively small number of participants with valgus alignment. Moreover, only 0.8% of the variations of the negative KAM were explained by the mechanical alignment in the multiple regression analysis. Further research enrolling more subjects with valgus alignment would reveal the relationship between the amount of valgus and the negative KAM-time integral.

Our study has several limitations. First, though we explored the relationship between the KAM-time integral and the maximum KAM and the radiographic alignment variables, no causality relation could be directly inferred due to the cross-sectional nature of the study. Second, because randomly-selected volunteers were enrolled in the study, our findings may not be directly applicable to the patients with knee OA whose cartilage status should also be taken into account when deciding the correction amount in HTO[41]. Third, R^2 values in our multiple regression analyses were too small. Inclusion of more factors such as foot progression angle, stride length, and walking speed might have improved the explanatory power of the regression model. Fourth, there were some inherent problems during radiographic assessments because the study was retrospective. Since radiographs such as the lateral and the Rosenberg view were not taken, K-L grade of tibiofemoral joint of each knee could be assessed merely from the full-lower limb standing anteroposterior (AP) radiograph, which could have underestimated the degree of OA. Moreover, in some radiographs, X-ray beam was not orthogonal to the tibiofemoral joint space, which made it difficult to assign the K-L grades properly and measure angles for some lower extremities.

In spite of its limitations, our study presented the associations between the positive KAM-time integral and the maximum KAM and radiographic alignment variables, namely, mTFA and AJLO in randomly-selected individuals. Moreover, we demonstrated the difference of the positive KAM-time integral and the maximum KAM in lower extremities with 3° to 8° of varus and 0° to 5° of valgus while there was no significant difference of

(a)

	mTFA ≥ 10	9 ≤ mTFA < 10	8 ≤ mTFA < 9	7 ≤ mTFA < 8	6 ≤ mTFA < 7	5 ≤ mTFA < 6	4 ≤ mTFA < 5	3 ≤ mTFA < 4	2 ≤ mTFA < 3	1 ≤ mTFA < 2	0 ≤ mTFA < 1	-1 ≤ mTFA < 0	-2 ≤ mTFA < -1	-3 ≤ mTFA < -2	-4 ≤ mTFA < -3	-5 ≤ mTFA < -4	-6 ≤ mTFA < -5	-7 ≤ mTFA < -6	-8 ≤ mTFA < -7
mTFA ≥ 10																			
9 ≤ mTFA < 10	-0.072 (1.000)																		
8 ≤ mTFA < 9	-0.011 (1.000)	-0.060 (1.000)																	
7 ≤ mTFA < 8	-0.073 (1.000)	0.001 (1.000)	0.061 (1.000)																
6 ≤ mTFA < 7	-0.085 (1.000)	0.013 (1.000)	0.073 (1.000)	0.012 (1.000)															
5 ≤ mTFA < 6	-0.091 (1.000)	0.019 (1.000)	0.080 (1.000)	0.019 (1.000)	0.006 (1.000)														
4 ≤ mTFA < 5	-0.101 (1.000)	0.030 (1.000)	0.090 (1.000)	0.029 (1.000)	0.017 (1.000)	0.010 (1.000)													
3 ≤ mTFA < 4	-0.113 (1.000)	0.041 (1.000)	0.101 (1.000)	0.040 (1.000)	0.028 (1.000)	0.021 (1.000)	0.011 (1.000)												
2 ≤ mTFA < 3	-0.124 (1.000)	0.052 (1.000)	0.113 (1.000)	0.052 (0.503)	0.039 (0.318)	0.033 (1.000)	0.023 (0.344)	0.012 (1.000)											
1 ≤ mTFA < 2	0.129 (1.000)	0.058 (1.000)	0.118 (1.000)	0.057 (0.173)	0.045 (0.067)	0.038 (0.874)	0.028 (0.020)	0.017 (1.000)	0.005 (1.000)										
0 ≤ mTFA < 1	0.138 (1.000)	0.066 (1.000)	0.127 (1.000)	0.065 (0.027)	0.053 (0.004)	0.047 (0.104)	0.037 (<0.001)	0.025 (0.016)	0.014 (1.000)	0.009 (1.000)									
-1 ≤ mTFA < 0	0.146 (0.638)	0.075 (1.000)	0.135 (1.000)	0.074 (0.004)	0.062 (<0.001)	0.055 (0.011)	0.045 (<0.001)	0.034 (<0.001)	0.022 (0.075)	0.017 (1.000)	0.008 (1.000)								
-2 ≤ mTFA < -1	0.157 (0.315)	0.086 (1.000)	0.146 (1.000)	0.085 (<0.001)	0.073 (<0.001)	0.066 (<0.001)	0.056 (<0.001)	0.045 (<0.001)	0.033 (<0.001)	0.028 (0.009)	0.019 (0.791)	-0.011 (1.000)							
-3 ≤ mTFA < -2	0.161 (0.249)	0.090 (1.000)	0.150 (0.529)	0.089 (<0.001)	0.077 (<0.001)	0.070 (<0.001)	0.060 (<0.001)	0.049 (<0.001)	0.037 (<0.001)	0.032 (0.008)	0.023 (0.456)	-0.015 (1.000)	-0.004 (1.000)						
-4 ≤ mTFA < -3	0.169 (0.178)	0.097 (1.000)	0.157 (0.383)	0.096 (<0.001)	0.084 (<0.001)	0.077 (0.001)	0.067 (<0.001)	0.056 (<0.001)	0.045 (0.021)	0.039 (0.119)	0.031 (1.000)	-0.022 (1.000)	-0.011 (1.000)	-0.007 (1.000)					
-5 ≤ mTFA < -4	0.169 (0.201)	0.098 (1.000)	0.158 (1.000)	0.097 (0.002)	0.085 (0.001)	0.078 (0.007)	0.068 (0.001)	0.057 (0.022)	0.045 (0.334)	0.040 (1.000)	0.031 (1.000)	-0.023 (1.000)	-0.012 (1.000)	-0.008 (1.000)	-0.001 (1.000)				
-6 ≤ mTFA < -5	0.109 (1.000)	0.037 (1.000)	0.098 (1.000)	0.037 (1.000)	0.024 (1.000)	0.018 (1.000)	0.008 (1.000)	-0.003 (1.000)	-0.015 (1.000)	-0.020 (1.000)	-0.029 (1.000)	0.037 (1.000)	0.048 (1.000)	0.052 (1.000)	0.059 (1.000)	0.060 (1.000)			
-7 ≤ mTFA < -6	-0.063 (1.000)	-0.135 (1.000)	-0.074 (1.000)	-0.135 (1.000)	-0.148 (0.729)	-0.154 (0.515)	-0.164 (0.202)	-0.175 (0.089)	-0.187 (0.037)	-0.192 (0.024)	-0.201 (0.012)	0.209 (0.006)	0.220 (0.002)	0.224 (0.002)	0.231 (0.001)	0.232 (0.002)	0.172 (0.886)		

	mTFA≥10	9≤mTFA<10	8≤mTFA<9	7≤mTFA<8	6≤mTFA<7	5≤mTFA<6	4≤mTFA<5	3≤mTFA<4	2≤mTFA<3	1≤mTFA<2	0≤mTFA<1	-1≤mTFA<0	-2≤mTFA<-1	-3≤mTFA<-2	-4≤mTFA<-3	-5≤mTFA<-4	-6≤mTFA<-5	-7≤mTFA<-6	-8≤mTFA<-7
-8≤mTFA<-7	0.187 (0.405)	0.115 (1.000)	0.176 (0.738)	0.115 (0.605)	0.102 (1.000)	0.096 (1.000)	0.086 (1.000)	0.075 (1.000)	0.063 (1.000)	0.058 (1.000)	0.049 (1.000)	0.041 (1.000)	0.030 (1.000)	0.026 (1.000)	0.019 (1.000)	0.018 (1.000)	0.078 (1.000)	0.250 (0.009)	

(b)

	mTFA≥10	9≤mTFA<10	8≤mTFA<9	7≤mTFA<8	6≤mTFA<7	5≤mTFA<6	4≤mTFA<5	3≤mTFA<4	2≤mTFA<3	1≤mTFA<2	0≤mTFA<1	-1≤mTFA<0	-2≤mTFA<-1	-3≤mTFA<-2	-4≤mTFA<-3	-5≤mTFA<-4	-6≤mTFA<-5	-7≤mTFA<-6	-8≤mTFA<-7
mTFA≥10																			
9≤mTFA<10	-0.164 (1.000)																		
8≤mTFA<9	0.002 (1.000)	-0.166 (1.000)																	
7≤mTFA<8	-0.178 (1.000)	0.014 (1.000)	0.180 (1.000)																
6≤mTFA<7	-0.177 (1.000)	0.013 (1.000)	0.179 (1.000)	-0.001 (1.000)															
5≤mTFA<6	-0.215 (1.000)	0.051 (1.000)	0.217 (1.000)	0.037 (1.000)	0.038 (1.000)														
4≤mTFA<5	-0.227 (1.000)	0.063 (1.000)	0.229 (1.000)	0.050 (1.000)	0.050 (1.000)	0.012 (1.000)													
3≤mTFA<4	-0.249 (1.000)	0.085 (1.000)	0.251 (1.000)	0.071 (1.000)	0.072 (1.000)	0.034 (1.000)	0.021 (1.000)												
2≤mTFA<3	-0.273 (1.000)	0.109 (1.000)	0.275 (1.000)	0.095 (1.000)	0.096 (0.114)	0.058 (1.000)	0.046 (0.917)	0.024 (1.000)											
1≤mTFA<2	0.283 (1.000)	0.119 (1.000)	0.285 (1.000)	0.106 (1.000)	0.106 (0.027)	0.068 (1.000)	0.056 (0.097)	0.035 (1.000)	0.010 (1.000)										
0≤mTFA<1	0.306 (1.000)	0.142 (1.000)	0.308 (1.000)	0.128 (0.153)	0.129 (0.001)	0.091 (0.484)	0.078 (<0.001)	0.057 (0.015)	0.033 (1.000)	0.022 (1.000)									
-1≤mTFA<0	0.322 (0.733)	0.158 (1.000)	0.324 (0.693)	0.144 (0.036)	0.145 (<0.001)	0.107 (0.088)	0.094 (<0.001)	0.073 (<0.001)	0.049 (0.101)	0.038 (1.000)	0.016 (1.000)								
-2≤mTFA<-1	0.348 (0.348)	0.184 (1.000)	0.350 (0.328)	0.170 (0.003)	0.171 (<0.001)	0.133 (0.004)	0.121 (<0.001)	0.099 (<0.001)	0.075 (<0.001)	0.065 (0.005)	0.042 (1.000)	-0.026 (1.000)							
-3≤mTFA<-2	0.363 (0.227)	0.199 (1.000)	0.365 (0.214)	0.185 (0.001)	0.186 (<0.001)	0.148 (0.001)	0.136 (<0.001)	0.114 (<0.001)	0.090 (<0.001)	0.080 (0.001)	0.057 (0.171)	-0.041 (1.000)	-0.015 (1.000)						
-4≤mTFA<-3	0.367 (0.236)	0.203 (1.000)	0.369 (0.222)	0.189 (0.004)	0.190 (<0.001)	0.152 (0.009)	0.140 (<0.001)	0.118 (0.001)	0.094 (0.048)	0.084 (0.201)	0.061 (1.000)	-0.045 (1.000)	-0.019 (1.000)	-0.004 (1.000)					
-5≤mTFA<-4	0.391	0.227 (1.000)	0.393	0.213	0.214	0.176	0.164	0.142	0.118	0.108	0.085	-0.070	-0.043	-0.028	-0.024				

8

	mTFA≥10	9≤mTFA<10	8≤mTFA<9	7≤mTFA<8	6≤mTFA<7	5≤mTFA<6	4≤mTFA<5	3≤mTFA<4	2≤mTFA<3	1≤mTFA<2	0≤mTFA<1	-1≤mTFA<0	-2≤mTFA<-1	-3≤mTFA<-2	-4≤mTFA<-3	-5≤mTFA<-4	-6≤mTFA<-5	-7≤mTFA<-6	-8≤mTFA<-7
-6≤mTFA<-5	0.259 (0.133)	0.095 (1.000)	0.261 (0.125)	0.081 (0.002)	0.082 (<0.001)	0.044 (0.006)	0.032 (<0.001)	0.010 (0.003)	-0.014 (0.050)	-0.024 (0.157)	-0.047 (1.000)	0.063 (1.000)	0.089 (1.000)	0.104 (1.000)	0.108 (1.000)	0.132 (1.000)			
-7≤mTFA<-6	0.056 (1.000)	-0.108 (1.000)	0.058 (1.000)	-0.122 (1.000)	-0.121 (1.000)	-0.159 (1.000)	-0.171 (1.000)	-0.193 (1.000)	-0.217 (1.000)	-0.227 (1.000)	-0.250 (1.000)	0.266 (1.000)	0.292 (1.000)	0.307 (1.000)	0.311 (1.000)	0.335 (0.678)	0.203 (1.000)		
-8≤mTFA<-7	0.435 (0.263)	0.271 (1.000)	0.437 (0.251)	0.257 (0.568)	0.258 (0.345)	0.220 (1.000)	0.208 (1.000)	0.186 (1.000)	0.162 (1.000)	0.152 (1.000)	0.129 (1.000)	0.113 (1.000)	0.087 (1.000)	0.072 (1.000)	0.068 (1.000)	0.044 (1.000)	0.176 (1.000)	0.379 (0.985)	

Table 5. Results of the post-analysis of ANOVA of the KAM variables according to the alignment groups of one-degree interval. (a) Positive KAM-time integral (b) Maximum KAM. Differences are reported and P-values are written in parentheses. *mTFA* mechanical tibiofemoral angle.

Interobserver reliability of radiographic measurements	ICC
Medial K-L grade (0/I/II/III/IV)	0.823 (95% CI, 0.671–0.909)
Lateral K-L grade (0/I/II/III/IV)	1
mTFA (°)	0.996 (95% CI, 0.991–0.998)
MPTA (°)	0.949 (95% CI, 0.898–0.974)
LDFA (°)	0.98 (95% CI, 0.96–0.99)
KJLO (°)	0.966 (95% CI, 0.93–0.984)
AJLO (°)	0.987 (95% CI, 0.974–0.994)
JLCA (°)	0.879 (95% CI, 0.763–0.94)
Tibiofemoral translation	0.986 (95% CI, 0.97–0.993)

Table 6. Interobserver reliability of radiographic measurements. *ICC* intraclass correlation coefficient, *CI* confidence interval, *K-L* Kellgren-Lawrence, *mTFA* mechanical tibiofemoral angle, *MPTA* medial proximal tibial angle, *LDFA* lateral distal femoral angle, *KJLO* knee joint line orientation, *AJLO* ankle joint line orientation, *JLCA* joint line convergence angle.

the KAM within the latter alignment groups. We believe these findings would provide biomechanical evidence to correction to at least neutral alignment when performing HTO while valgus overcorrection provides no additional benefit in reducing the KAM.

Methods
Participants
This study was performed by retrospectively reviewing the data from a previously-conducted prospective cohort study[42]. 500 participants with the age of 10 to 75 years were randomly selected from the city of Seongnam, Gyeonggi province, South Korea. All subjects gave informed consent about data collection. They underwent 3D gait analysis and standing full-lower limb AP radiograph was taken for each individual from February 2016 to December 2019. The present study was approved by the institutional review board of Seoul National University Bundang Hospital (B-2308-847-102) and was performed according to the international ethical guidelines of human subject research.

Of 1000 lower extremities from total 500 participants, 937 were included in the final analysis. Since the position of the patella relative to the center of the knee joint could substantially affect radiographic parameters such as mTFA, medial proximal tibial angle (MPTA), and mechanical lateral distal femoral angle (LDFA)[43], quality of each full-lower limb AP radiograph was evaluated in relation to the degree of patellar rotation relative to the adjacent femur. The relative amount of patellar rotation was categorized into 4 grades in the following way. When the patella was located at the center of the tibiofemoral joint, it was defined as "patella facing forward" or grade 0. If the edge of the patella crossed either the medial or lateral margin of the adjacent femur, it was termed grade 3 internal or external rotation, respectively. Grade 1 was assigned to those with only slight rotation from the center and grade 2 to those in which the patellar margin was just on but not past the boundary of the adjoining femur. 57 lower extremities with grade 3 patellar rotation were excluded from the analysis. Gait analysis data from 3 participants (6 lower extremities) were excluded due to marker mismatch error.

Anthropometric parameters
Age, sex, and anthropometric parameters such as height, weight, and body mass index (BMI) were collected from each participant.

Radiographic measurements
All full-lower limb standing AP radiograph images were uploaded to a picture archiving and communication system (PACS), and radiographic measurements were conducted with the PACS softwares (INFINITT, Seoul, Korea and Medixant. RadiAnt DICOM Viewer. Version 2023. 1.).

The degree of knee OA in the medial and lateral compartments of the tibiofemoral joint was evaluated using the K-L grade. For fear of ambiguity of the original definition and interobserver disagreement, we categorized less than 50% narrowing of the original joint space as K-L grade II and more than 50% narrowing of the joint space as K-L grade III[10].

The following radiographic alignment parameters were measured for each lower extremity in the standing full-lower limb AP radiograph: mTFA, MPTA, mechanical LDFA, knee joint line orientation (KJLO) relative to the horizontal plane, AJLO to the horizontal plane, and joint line convergence angle (JLCA). The mTFA, defined as the angle between the mechanical axis of the femur and the tibia, was measured in the following manner using the PACS softwares. The mechanical axis of the femur was depicted as the line from the center of the femoral head to the center of the intercondylar notch of the femur. Initially, a closest-fit circle was drawn to match the margin of the femoral head. The femoral head center was then determined as the intersection of the two crossing lines each with the length of the diameter of the circle. The mechanical axis of the tibia was referred to as the line connecting the center of the intercondylar eminences of the tibial plateau and the center of the talar dome. Positive and negative values of the mTFA were assigned to the knees with varus and valgus mechanical alignments, respectively. The MPTA was measured as the medial angle between the mechanical axis of the tibia and the tangential line to the tibial plateau. The mechanical LDFA was measured as the lateral angle between
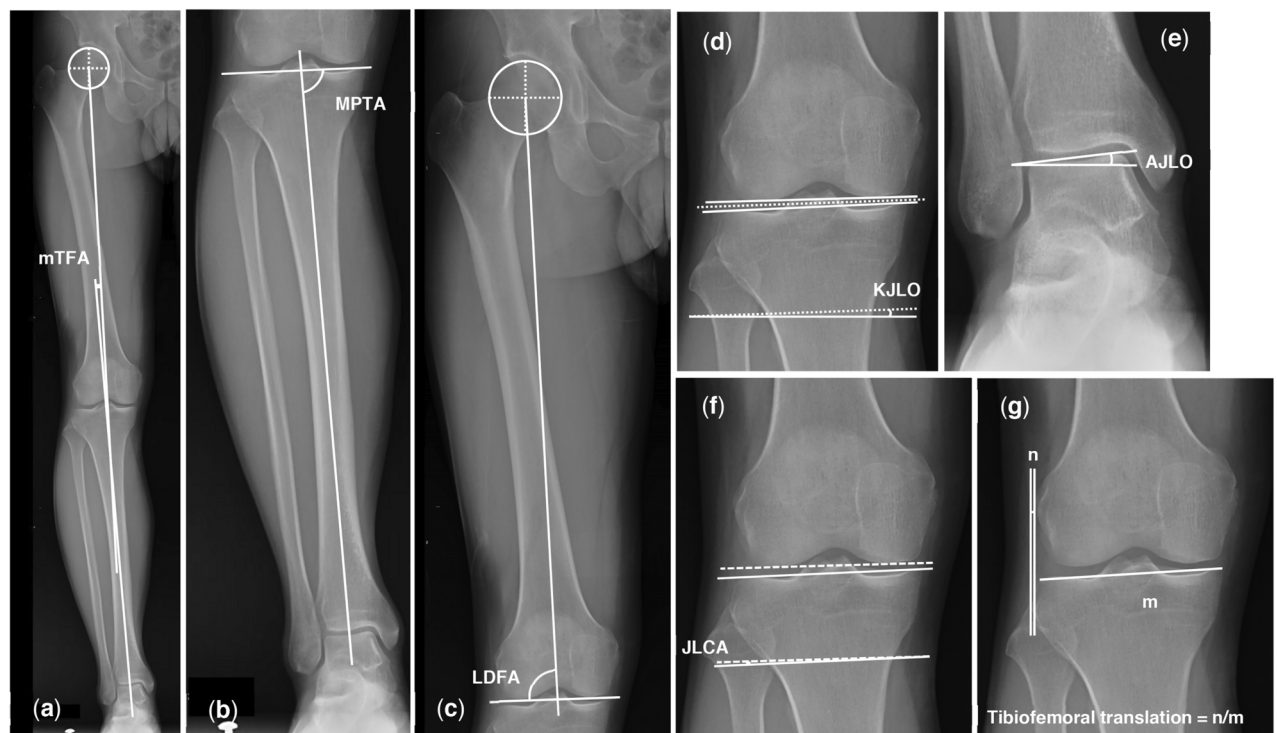
Fig. 1. Measurement of mTFA, MPTA, LDFA, KJLO, AJLO, JLCA, and tibiofemoral translation. (**a**) mTFA (**b**) MPTA (**c**) LDFA (**d**) KJLO (**e**) AJLO (**f**) JLCA (**g**) Tibiofemoral translation. *mTFA* mechanical tibiofemoral angle, *MPTA* medial proximal tibial angle, *LDFA* lateral distal femoral angle, *KJLO* knee joint line orientation, *AJLO* ankle joint line orientation, *JLCA* joint line convergence angle.

the mechanical axis of the femur and the tangential line to both the medial and lateral femoral condyles. The KJLO was measured in the following two steps. Initially, the midline of the tangential line to the tibial plateau and the tangential line to the femoral condyles was drawn. Then, the angle between this midline and a horizontal line parallel to the ground was defined as the KJLO. Positive and negative values were given when the midline was inclined to the medial and lateral sides of the corresponding tibiofemoral joint, respectively. The AJLO was defined as the angle between the tangential line to the talar dome and a horizontal line parallel to the ground. Positive and negative values were given when the tangential line was inclined to the medial and lateral sides of the corresponding tibiotalar joint, respectively. The JLCA was measured as the angle between the tangential line to the tibial plateau and the tangential line to the femoral condyles (Fig. 1). Positive and negative values were given when the intersection of the lines was located medial and lateral to the joint, respectively.

Tibiofemoral translation was measured using coronal tibiofemoral subluxation. It is known to impair the load transmission across the medial compartment of the knee[44] and to be caused by a difference in the medial and lateral soft tissue laxity[45]. It is defined as the distance between a line perpendicular to the ground and passing through the most lateral point of the lateral femoral condyle and a line perpendicular to the ground and passing through the most lateral point of the lateral tibial condyle. This distance was normalized by dividing it with the width of the corresponding tibial plateau[44] (Fig. 1). Positive and negative values were conferred when the lateral-most point of the femoral condyle was located medial and lateral to the lateral-most point of the tibial plateau, respectively.

Interobserver reliability was tested by two orthopaedic surgeons with 8 and 5 years of clinical experience in the orthopaedic department. To achieve adequate power, 33 lower extremities were randomly selected from the study population and assigned to each surgeon. They independently evaluated the K-L grade and measured the radiographic alignment parameters, being blinded to each other's measurements.

3D gait analysis

Participants underwent 3D gait analysis using a motion analysis system (Motion Analysis Corporation, Santa Rosa, California, USA) with 10 cameras at 120 frames per second and two force plates. Photo-reflective skin markers in accordance with Helen marker set were installed by an operator having 9 years of experience in the field. The participants walked barefoot on a ten-meter-long track at their self-selected speed after 10 walking trials. Joint moments were calculated using the inverse dynamic model and the global coordination system[42]. The values of the KAM-time integral and the maximum KAM in the stance phase were obtained. Although there can be the second peak KAM as well as the first peak KAM, the appearance of the second peak KAM is reported to be inconsistent[38]. Therefore, only the maximum KAM was used in our study. The KAM-time integral or KAM impulse which was reported to be more sensitive at distinguishing disease severities than the maximum KAM[9]

was calculated by integrating the KAM relative to time during the stance phase, representing accumulation of the KAM according to time. The positive and negative KAM-time integral values were calculated separately to represent the adduction and abduction moment, respectively[46]. Average values of 3 repetitive measurements of both the KAM-time integral and the maximum KAM were used in the analysis. The KAM-time integral and the maximum KAM were calculated in the units of N·m·s/kg and N·m/kg, respectively.

Statistical analysis

Descriptive statistical analyses were conducted first to depict the population characteristics. Normality was checked using the Kolmogorov–Smirnov test. Inferential statistical analyses were then performed using chi-square tests or Fisher's exact tests for categorical variables and one-way analyses of variance (ANOVA) and t-tests or Mann–Whitney test for continuous variables which belong to each alignment category by the interval of 1° of mTFA and either sex, respectively. Subgroup analyses for ANOVA were performed using Bonferroni post-hoc test. The correlation analyses between the KAM values and other variables were performed to obtain Pearson's product-moment correlation coefficient. Interobserver reliability was tested with intraclass correlation coefficients (ICCs) with the assumption of single measurement and absolute agreement. The multiple linear regression analyses for the KAM values were conducted with variables which were significantly related to the KAM values in the correlation analyses. Then, backward elimination of variables was performed so that only variables with independent explanatory ability wound remain in the final model. To point out variables with the highest explanatory value, more backward eliminations from the final model for the positive KAM-time integral and the maximum KAM were conducted. Multi-collinearity was evaluated with variance inflation factors (VIFs). All statistical analyses were done using R software (version 4.2.3; R Foundation for Statistical Computing, Vienna, Austria), RStudio 2023.12.0 + 369 "Ocean Storm" Release (33206f75bd14d07d84753f965eaa24756eda97b7, 2023-12-17) for Windows. In every analysis, P-values less than 0.05 were considered as statistically significant.

Data availability

The data that support the findings of this study are not openly available because the study participants did not consent to public sharing of their data. Moreover, the institutional review board of Seoul National University Bundang Hospital did not approve sharing of the participants' data publicly. The data are available from the corresponding author only upon reasonable request. Data are located in controlled access data storage at Seoul National University Bundang Hospital.

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Acknowledgements

Author contributions

K.S.K. contributed to radiographic measurements, data analysis, data interpretation, and drafting of the work. N.L. contributed to the design of the work, data analysis and data interpretation. K.M.L. contributed to data acquisition. C.B.C. contributed to the design of the work, data acquisition, and data interpretation. S.K. contributed to data interpretation.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-80161-3.

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