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Original article

Morphologic MRI changes of the anterior cruciate ligament are associated with an increase in the medial tibial plateau bony slope after medial opening wedge high tibial osteotomy in a non-injured ACL population

Oh-Jin Kwon [a], Jong-Min Kim [a,*], Seong-Il Bin [a], Bum-Sik Lee [a], Gi-Woon Yoon [a], Young-Hee Kwon [b]

[a] Department of Orthopedic Surgery, Asan Medical Center, University of Ulsan College of Medicines, Olympic-ro 43-gil, Songpa-gu, 05505 Seoul, South Korea
[b] Department of Nursing, Asan Medical Center, Olympic-ro 43-gil, Songpa-gu, 05505 Seoul, South Korea

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ABSTRACT

Background: Medial opening wedge high tibial osteotomy (OWHTO) is a useful treatment for medial osteoarthritis. However, OWHTO sometimes causes a change in tibial slope in the sagittal plane. Although several studies have described the effects of the tibial slope on the biomechanics of the knee, including the anterior cruciate ligament (ACL), there has been little study of the magnetic resonance imaging (MRI) visible changes occurring to the native ACL and the factors affecting them after OWHTO.
Hypothesis: We hypothesized that morphologic MRI changes to an uninjured ACL after OWHTO would be associated with increased medial tibial plateau bony slope.
Patients and Methods: Thirty-three patients who underwent OWHTO and pre/postoperative MRI were included in this retrospective study. The mean period of follow-up MRI was 22.35 (±14.78) months. The patients were divided into two groups according to the occurrence of postoperative ACL morphologic MRI changes defined as mucoid degeneration, ganglion cyst occurrence, or change in the ACL fiber shape (stationary group $n = 21$, altered group $n = 12$). The medial tibial plateau bony slope (MTS) and anterior tibial translation (ATT) were evaluated on MRI. Logistic regression analysis was used to determine factors affecting the occurrence of postoperative ACL morphologic changes.
Results: Postoperative MTS and the difference between pre- and post values (ΔMTS), postoperative ATT and the difference between pre- and post values (ΔATT) were significantly different between stationary and altered groups. ΔMTS was associated with postoperative morphologic changes to the ACL (odds ratio: 0.30, 95% confidence interval = 0.11–0.82, $p = 0.019$).
Conclusion: The occurrence of morphologic ACL change after OWHTO is associated with the amount of MTS change.
Level of Evidence: III, Retrospective comparative study.

1. Introduction

High tibial osteotomy (HTO) is a useful treatment option for younger patients with early-stage medial compartmental osteoarthritis and varus knee. Surgical techniques for osteotomy include closing wedge HTO and opening wedge HTO (OWHTO) [1,2]. Although OWHTO has several complications, including an increased risk of delayed union and nonunion, the necessity of a bone graft, and loss of correction [3], OWHTO has been widely performed because it is a convenient technique (avoidance of proximal tibiofibular joint exposure, no requirement for fibular osteotomy and peroneal nerve dissection), development of devices for rigid fixation and less demanding of subsequent total knee replacement [2,4,5]. The purpose of OWHTO is to realign the knee into a valgus alignment in the coronal plane, and to therefore achieve a load distribution from the medial side to the lateral side of the knee. However, OWHTO can also change the tibial slope in the sagittal plane. The tibial slope is defined as the angle between the longitudinal line of the tibial diaphysis and the tangent line to the tibial plateau surface. Various methods for measuring the tibial slope

* Corresponding author.
E-mail address: jmkim@amc.seoul.kr (J.-M. Kim).

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on radiographs and magnetic resonance imaging (MRI) have been described; however, [6–9] as an alternative, the tibial bony slope measured on MRI can also reflect the tibial slope [10].

Although subject to some controversy, it is generally accepted that OWHTO tends to increase the tibial slope, [11–13] and several studies reported that an increased tibial slope contributes to non-contact anterior cruciate ligament (ACL) injury [14–16]. This phenomenon has been stated to be due to the increased tibial slope influencing the biomechanics of the knee in terms of the anterior translation of the tibia relative to the femur, increasing strain and loading in the ACL, and creating tibial shear force [17–19]. This phenomenon can also affect the knee in cases of reconstructed ACL or ACL insufficiency [20–24]. There is a few study evaluating the preoperative ACL status and its impact on clinical outcome. [25] However, no previous study has evaluated the postoperative morphologic changes to an uninjured ACL on MRI after OWHTO.

The purpose of our study was to use MRI to analyze changes to an uninjured ACL and to determine the factors affecting any changes of ACL on MRI after OWHTO. We hypothesized that morphologic changes to an uninjured ACL on MRI after OWHTO would be associated with increased medial tibial plateau bony slope (MTS).

2. Materials and Methods

2.1. Study design

Patients who underwent OWHTO for medial compartmental osteoarthritis from December 2009 to April 2017 were retrospectively reviewed. The inclusion criteria were patients who underwent an MRI examination before and after surgery, with a postoperative MRI taken at least 10 months after surgery. Follow-up rate of postoperative MRI was 21.6% (37/171) and mean period of follow-up MRI was 22.35 (±14.78) months. Because of the retrospective design, the timing of postoperative MRI was not same for each patient. The exclusion criteria were (1) history of an ACL injury and (2) underwent ACL reconstruction (including revision surgery) before or after OWHTO. A total of 37 patients were identified. Of the 37 patients, four were excluded, leaving 33 patients for inclusion in this study (Fig. 1).

First, patients were divided into stationary and altered ACL groups according to postoperative morphologic ACL changes on MRI. Then, the radiologic parameters were measured for comparative analysis and evaluation of the risk factors affecting an uninjured ACL changes after surgery. The radiologic parameters included hip-knee-ankle angle (HKA) and medial proximal tibial angle (MPTA) on the whole-leg standing radiograph, and MTS and anterior tibial translation (ATT) on MRI. The pre- and postoperative parameters were measured and differences between them were calculated.

The MTS and ATT were measured on MRI. ACL changes were assessed and compared between preoperative and postoperative MRI. MRI examinations were performed on a 3.0-T MR scanner (Achieva 3T, Philips Healthcare). T2-weighted sagittal images with a 1.5 mm slice thickness were acquired and used. A digital caliper tool available on the PACS was used to perform measurements on radiographs and MRI. The caliper could measure angles with a precision of up to 1° and distances up to the second decimal place.

Intra-observer and inter-observer reliability in the radiologic measurements were assessed using intraclass correlation coefficients (ICC). Two orthopedic surgeons independently measured the radiologic parameters, one being an author of this study and the other being an independent orthopedic surgeon who did not otherwise participate in this study. The radiograph and MRI parameters were measured blindly to each other. The ICCs for radiologic measurements were greater than 0.80 (range: 0.948–0.998) and the measurements of just one of the investigators were used for the analysis. Cohen's kappa (κ)-values were measured to assess intra-observer and inter-observer agreement for determining the morphologic changes of ACL on MRI. The κ-value of intra-observer agreement was 0.869 and that of inter-observer agreement was 0.807, which were indicating excellent agreement by Landis and Koch [26]. This study was approved by the institutional review board of our hospital.

2.2. Measurements and assessments

2.2.1. Hip-knee-ankle angle (HKA) and medial proximal tibial angle (MPTA)

HKA and MPTA were measured on whole-leg standing radiographs. The HKA was defined as the angle formed by lines connecting the hip-knee center and knee-ankle center [27,28]. The MPTA was defined as the medial angle formed between the line of the mechanical tibial axis and a line tangent to the joint surface of the proximal tibial plateau [28].

2.2.2. Medial tibial plateau bony slope (MTS) and anterior tibial translation (ATT)

MRI images were used for the measurement of MTS and ATT. As it is difficult to distinguish the medial and lateral bony slope accurately on simple lateral radiographs [10], the bony slope angle was measured on sagittal MRI images. ATT refers to the relative sagittal position of the proximal tibia in respect to the distal femur with the subject in a resting supine position, which was the posture adopted by the patients during the MRI exam. It does not mean

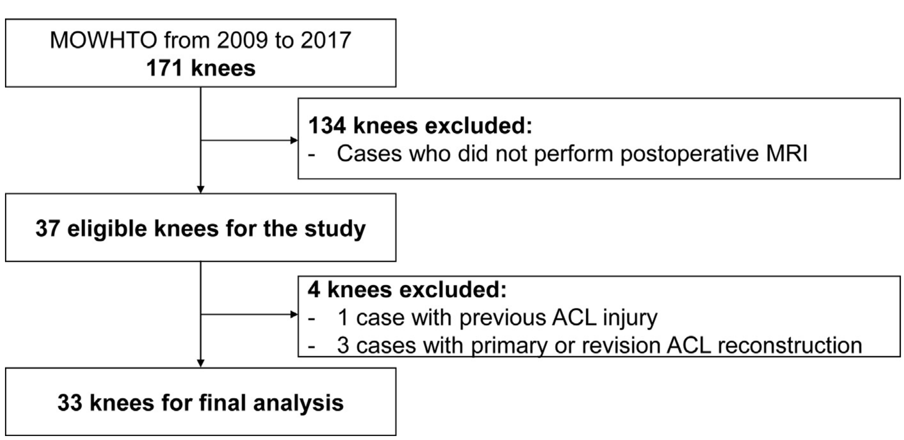

Fig. 1. Flow chart of participants for the study. MOWHTO, medial opening wedge high tibial osteotomy; MRI, magnetic resonance imaging; ACL, anterior cruciate ligament.

anterior instability as in an anterior translation of the tibia in an ACL injury.

MTS was measured on the MRI sagittal image, as described by Lustig et al. [10] A vertical line representing the tibial anatomical axis was created in the central sagittal section of the tibia. This image shows ACL fibers and tibial tuberosity. The line was drawn by connecting two points: the first being the mid-point between the anterior and posterior cortices at the level of tibial tuberosity, and the second being the mid-point created by the same method 3–5 cm below the level of the first point. A line representing the medial tibial plateau slope was then created on the mid-sagittal section of the medial tibial plateau. This line was drawn at a tangent to the most proximal bony points in the anterior and posterior portions of the medial tibial plateau. Thus, the MTS is the angle between the vertical and tangential lines (Fig. 2). A decrease in this MTS angle reflects an increase in the posterior tibial slope.

ATT was measured on the mid-sagittal MR image of the medial tibial plateau, as described by Vahey et al. [29] First, a line parallel to the long axis of the PACS image was drawn on the most posterior portion of the medial femoral condyle. A second parallel line was then drawn in the medial tibial plateau. The ATT was then defined as the distance between these two parallel lines (Fig. 3).

2.2.3. Assessment of postoperative morphologic ACL change on MRI

The morphologic changes to the ACL were assessed on pre- and postoperative sagittal MR images. We defined the morphologic change of ACL as mucoid degeneration, ganglion cyst occurrence, or change in the ACL fiber shape on postoperative MRI. Mucoid degeneration refers to thickened ill-defined fibers or increased signal intensity on postoperative proton density-weighted images compared with preoperative images [30,31] (Fig. 4). A ganglion cyst of ACL refered to a new occurrence of fluid signal in the substance of the ligament with a mass effect on ACL fibers or lobulated margins [30] (Fig. 5). Change in the ACL fiber shape was defined as a loss of preoperative straight form (Fig. 6). Patients with the defined ACL changes on postoperative MRI compared with preoperative MRI were classified as “Altered ACL”, while those who did not show changes were classified as ‘Stationary ACL’.

2.3. Statistical analysis

All statistical analyses were performed using SPSS for Windows (version 18.0; SPSS, Inc., IBM, Chicago, IL, USA). The Kolmogorov-Smirnov test was performed to determine whether parametric

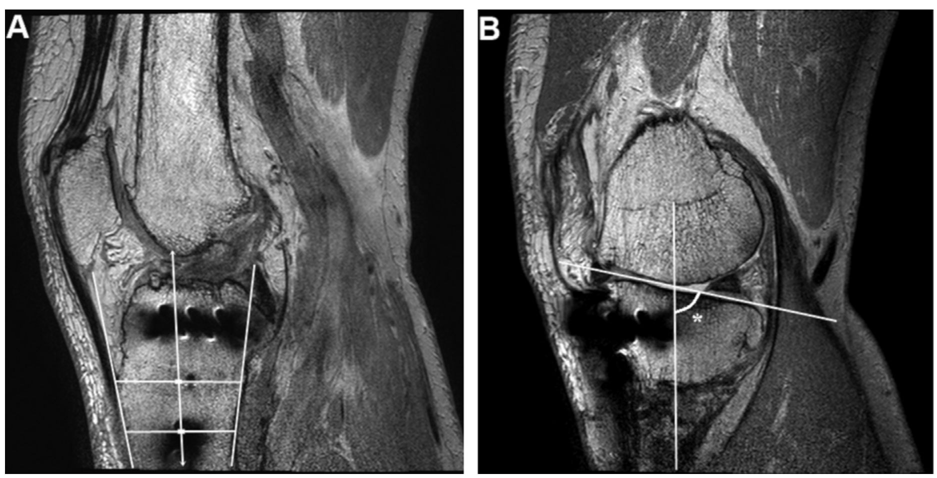

Fig. 2. Measurement of the medial tibial plateau bony slope (MTS). (A) The tibial anatomical axis (vertical line) was drawn to connect two mid-points between the anterior and posterior tibial cortex on the central sagittal section image of the entire tibial plateau. (B) The articular surface line of the medial tibial plateau (tangential line) was drawn to connect the two points between the most superior bony points of the anterior and posterior portions of the medial tibial plateau on the mid-sagittal section image. The angle (*) is the MTS angle.

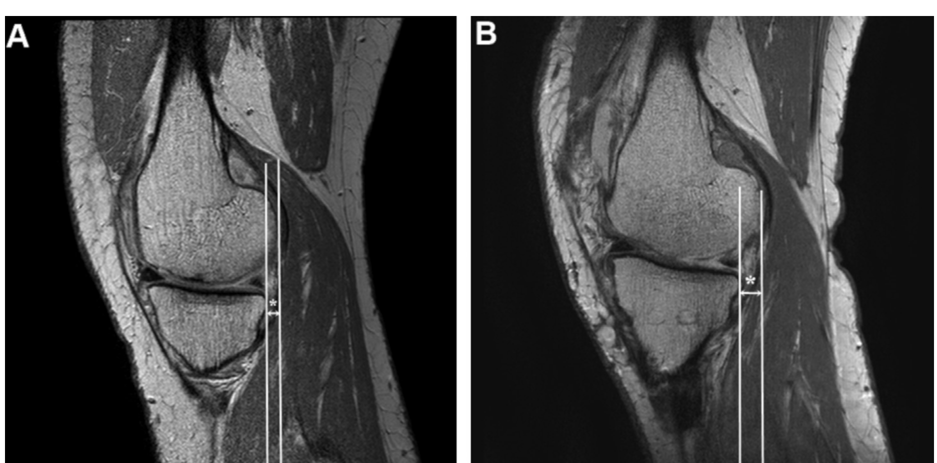

Fig. 3. Measurement of the anterior tibial translation (ATT) preoperatively (A) and postoperatively (B). Two lines parallel to the long axis of the PACS image are drawn, at tangents to the most posterior portion of the medial femoral condyle and medial tibial plateau on a mid-sagittal section image of the medial tibial plateau. The distance (*) is the ATT distance. This case shows an increase in ATT after surgery.

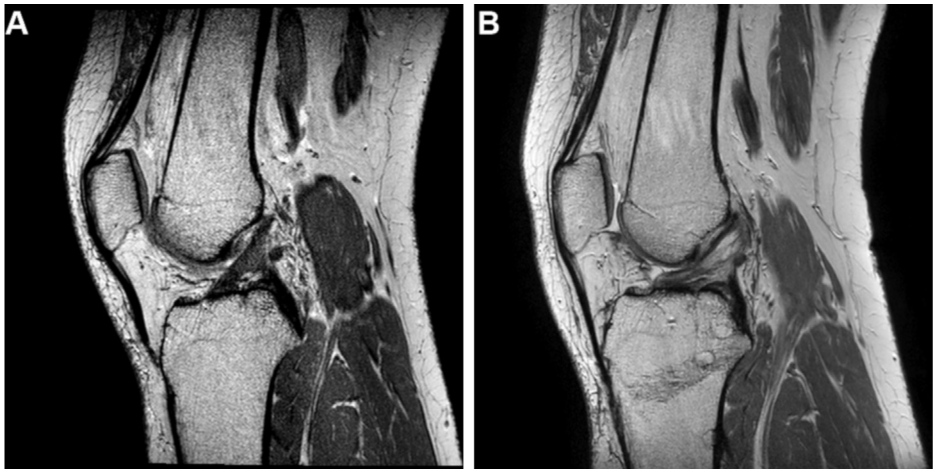

Fig. 4. Example of postoperative morphologic ACL change: mucoid degeneration (left side of knee) (A) preoperative sagittal MRI image, (B) postoperative sagittal MRI image. (Postoperative image also shows a ganglion cyst in an ACL).

Fig. 5. Example of postoperative morphological ACL change: ganglion cyst (left side of knee) (A) preoperative sagittal MRI image, (B) postoperative sagittal MRI image.

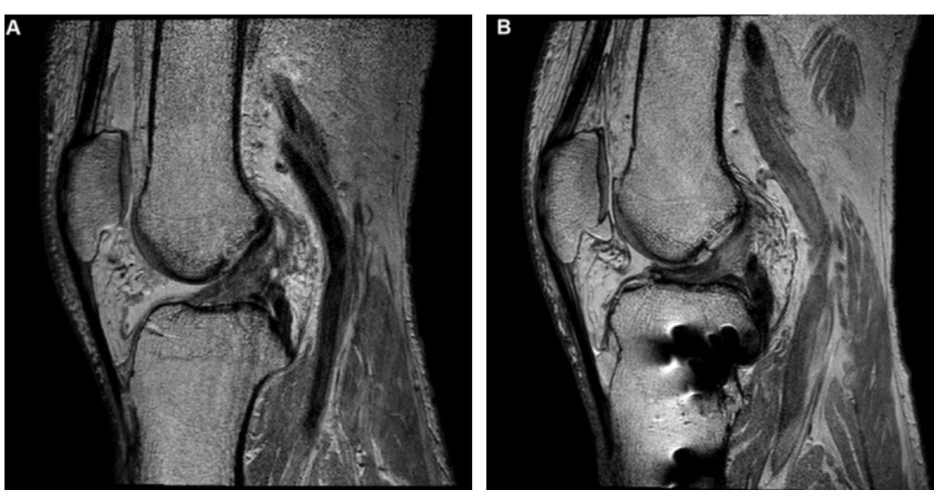

Fig. 6. Example of postoperative morphological ACL change: change of ACL fiber shape (right side of knee) (A) preoperative sagittal MRI image (B), postoperative sagittal MRI image.

or non-parametric statistical methods were appropriate. Comparisons of continuous variables from the demographic data were performed using independent *t*-tests or Mann–Whitney tests (age, BMI, time from surgery to post-MRI). Categorical variables were analyzed using Fisher's exact test (gender), Pearson's Chi^2 test (operative side), or a Mann-Whitney test (medial compartment cartilage status-WORMS [whole-organ magnetic resonance imaging score] grade [32]). Preoperative and postoperative radiologic parameters and differences between them (HKA, MPTA, MTS, ATT) were compared between the stationary and altered ACL

Table 1
Demographic data of the patients.

	Stationary ACL (n = 21)	Altered ACL (n = 12)	p-Value
Age, years (SD, range)	48.81 (12.02, 25–69)	54.50 (11.95, 29–71)	0.199
Gender, male:female (%)	15(71.4):6(28.6)	6(50):6(50)	0.274
BMI, kg/m^2 (SD, range)	26.85 (2.31, 22.93–31.90)	25.81 (2.29, 22.63–29.65)	0.223
Operative side, Right:Left (%)	8(38.1):13(61.9)	6(50):6(50)	0.459
Medial compartment cartilage status – WORMS grade, (number)			
Preoperative	0/6/0/3/1/0/11	0/2/1/0/1/2/6	0.754
Postoperative	0/5/1/2/1/1/11	0/2/1/1/0/0/8	0.567
Time from surgery to post-MRI, months (SD, range)	18.43 (9.76, 10–48)	29.67 (19.79, 11–70)	0.308
Mean postoperative HSS scores (SD, range)	90.25 (7.27, 75–97)	92.45 (6.20, 85–100)	0.427

ACL: anterior cruciate ligament, WORMS: whole-organ magnetic resonance imaging score, grade 0/1/2/3/4/5/6, HSS: Hospital for Special Surgery Knee score.

groups using independent t-tests and Mann–Whitney tests. The selected variables to determine the risk factors were age, BMI, time from surgery to post-MRI, WORMS grade of medial compartment cartilage (preoperative, postoperative), HKA (preoperative, postoperative, difference), MPTA (preoperative, postoperative, difference), MTS (preoperative, postoperative, difference), ATT (preoperative, postoperative, difference). The significant risk factors were selected using univariate logistic regression analysis, and binary logistic regression analysis with enter method was performed to determine the factors affecting the occurrence of postoperative morphological ACL changes. A p value < 0.05 was considered statistically significant. G-Power 3.1.5 software was used to perform the post hoc analysis for the multivariate logistic regression. The power of this study was 86% with a type I error of 0.05, a sample size of 33, and OR and R-squared attributed to independent variables.

3. Results

A total of 33 patients were classified according to postoperative ACL change on MRI. Postoperative ACL changes showed 9 cases of mucoid degeneration, 5 cases of ganglion cyst and 6 cases of change in the ACL fiber shape (6 patients had overlapped changes). Thus, patients were allocated to the stationary ACL group (n = 21) or the altered ACL group (n = 12). The patients' demographic data are shown in Table 1. There were no significant differences between the two groups.

Results of the comparative analyses of the coronal radiograph parameters between 2 groups are shown in Table 2. Preoperative and postoperative HKA and MPTA, and the differences between them, did not differ significantly between 2 groups. Table 3 shows the results of comparative analyses of the sagittal MRI parameters between 2 groups. Preoperative MTS and ATT were not significantly different, whereas postoperative MTS and ΔMTS were significantly different between the stationary and altered ACL groups (79.76 ± 3.95° vs. 75.25 ± 3.19°, respectively, p = 0.002; −1.00 ± 1.87° vs. −5.92 ± 2.15°, respectively, p < 0.001), with the altered ACL group having lower postoperative MTS than the stationary ACL group. Postoperative ATT and ΔATT were also significantly different between the stationary and altered ACL groups (0.93 ± 5.04 mm vs. 4.76 ± 2.87 mm, respectively, p = 0.022; 1.33 ± 1.87 mm vs. 3.49 ± 1.82 mm, respectively, p = 0.003), with the altered ACL group having more anterior tibial translation than the stationary ACL group.

Table 2
Comparisons of X-ray parameters between stationary and altered ACL groups.

Parameters	Stationary ACL	Altered ACL	p-Value
HKA (°)			
Preoperative	7.71 ± 3.21	8.17 ± 2.37	0.674
Postoperative	−3.81 ± 2.36	−3.08 ± 3.20	0.461
Differences (Δ)	−11.52 ± 3.86	−11.25 ± 4.27	0.851
MPTA (°)			
Preoperative	84.57 ± 2.50	84.17 ± 2.33	0.868
Postoperative	94.14 ± 2.39	93.67 ± 3.73	0.671
Differences (Δ)	9.57 ± 3.01	9.50 ± 3.23	0.949

ACL: anterior cruciate ligament, HKA: hip-knee-ankle angle, a positive value means varus alignment and a negative value means valgus alignment, MPTA: medial proximal tibial angle.

Table 3
Comparison of sagittal MRI parameters between stationary and altered ACL groups.

Parameters	Stationary ACL	Altered ACL	p-Value
MTS (°)			
Preoperative	80.76 ± 3.97	81.17 ± 2.48	0.671
Postoperative	79.76 ± 3.95	75.25 ± 3.19	0.002
Differences (Δ)	−1.00 ± 1.87	−5.92 ± 2.15	< 0.001
ATT (mm)			
Preoperative	−0.39 ± 4.30	1.27 ± 1.45	0.069
Postoperative	0.93 ± 5.04	4.76 ± 2.87	0.022
Differences (Δ)	1.33 ± 1.87	3.49 ± 1.82	0.003

ACL: anterior cruciate ligament, MTS: medial tibial plateau bony slope, ATT: anterior tibial translation.

The results of the logistic regression analysis are shown in Table 4. Univariate analysis of the considered variables (age, BMI, time from surgery to post-MRI, medial compartment cartilage status, pre-, post-, and ΔHKA, pre-, post-, and ΔMPTA, pre-, post-, and ΔMTS, pre-, post-, and ΔATT) was performed, and post-MTS, ΔMTS, Post- ATT, ΔATT showed significant factors. Multivariate analysis showed that ΔMTS was the only factor significantly associated with the altered ACL group (odds ratio: 0.300, 95% CI = 0.110–0.823, p = 0.019), albeit with a low odds ratio.

4. Discussion

The most important finding of this study was that postoperative morphological changes to the ACL are associated with changes to the medial tibial plateau bony slope after OWHTO. To the author's knowledge, the present study is the first to report on morphological changes to an uninjured ACL on MRI after OWHTO.

Recently, Matsumoto et al reported that increased posterior tibial slope angle measured in a radiograph had a significant correlation with arthroscopic ACL degeneration.[33] They confirmed morphologic ACL changes such as thinning, poor synovial coverage, partial or complete tear in a second-look arthroscopy. On the other hand, we measured the sagittal slope as MTS and assessed morphologic ACL changes in MRI images, In our study, the changes in ACL were observed on MRI despite a short follow-up period (mean: 31.27 months). There were no significant differences in corrected alignment and the correction amount in the coronal plane (defined as HKA and MPTA) between the groups with or without postoperative ACL changes. However, changes in the sagittal plane alignment defined as MTS and ATT were different between the two groups. The difference between preoperative and postoperative MTS was

Table 4
Factors associated with the occurrence of postoperative ACL changes on MRI.

Variables	Univariate logistic regression			Multivariate logistic regression		
	OR	95% CI	*p* value	Adjusted OR	95% CI	*p* value
Postoperative MTS	0.712	0.553–0.917	0.008			
ΔMTS	0.296	0.124–0.708	0.006	0.300	0.110–0.823	0.019
Postoperative ATT	1.239	1.007–1.524	0.043			
ΔATT	1.971	1.160–3.348	0.012			

Univariate logistic regression was performed for age, BMI, time from surgery to postoperative MRI, pre-postoperative WORMS grade, pre-postoperative & ΔHKA (hip-knee-ankle angle), pre-postoperative & ΔMPTA (medial proximal tibial angle), pre-postoperative & ΔMTS (medial tibial plateau bony slope), pre-postoperative & ΔATT (anterior tibial translation). OR: odds ratio, CI: confidence interval.

shown to be a significant factor affecting the occurrence of postoperative morphological ACL change on MRI.

The tibial slope is an important factor for knee stability in the sagittal plane. Several studies reported that increased tibial slope was associated with ATT, and that this relationship affects the anteroposterior instability of the knee. Dejour et al. [22] analyzed medial ATT using the radiological Lachman test and the lateral monopodal stance test in normal and ACL-deficient knees. Both radiographic tests showed the occurrence of ATT in association with an increase in tibial slope. Torzilli et al. [34] performed a cadaver study to examine the effect of axial compressive loads and quadriceps muscle force on the tibiofemoral joint. They reported finding an anterior neutral position shift, which resulted from the tibia being constantly moved in the anterior direction when a joint-compressive load or quadriceps force was applied. They reasoned that the normally tilted tibial plateau made the anterior shear force, and that this would cause the anterior tibial translation of the proximal tibia. Giffin et al. [35] also reported an anterior shift of the tibia in the resting position according to an increase in tibial slope. These studies suggest that the degree and change of the tibial slope could affect the anterior tibial translation and relative position of the anterior cruciate ligament in normal knees.

The increase in tibial slope may contribute to the failure of the ACL in reconstructed ACL knees. Schuster et al. [24] performed combined HTO, ACL reconstruction, and chondral resurfacing surgery, and analyzed the reconstructed graft failure according to the tibial slope in clinical and arthroscopic evaluations. They reported that the graft failure rate was higher in a group with a tibial slope more than 12.5°. Li et al. [21] analyzed the relationship between the tibial slope and postoperative ATT in ACL reconstructions, and found an association between tibial slope and ATT. In summary, an increase in the tibial slope increases the risk of ATT, and this phenomenon may affect change in the ACL.

In our study, on the other hand, we did not analyze changes of ACL graft in combined HTO and ACL reconstruction surgery, but focused on the morphologic change of an uninjured ACL change on MRI after OWHTO. The altered ACL group showed greater increase in the MTS and ATT. These findings are similar to previously reported studies. We measured MTS and ATT using MR images, and found a difference in ATT in the resting supine position without axial loading. If physiological axial loading is applied constantly with increased ATT during normal knee activity, the ACL loading and strain may increase, and there is the possibility of morphological changes to the ACL, which could be observed on an imaging study such as MRI. The surgeon should be careful during surgical procedures to maintain posterior tibial slope and prevent unexpected ACL changes [36,37].

This study has several limitations. First, the study design is of a retrospective nature and does not analyze the biomechanics of the knee. Thus, this study does not identify the exact mechanism of postoperative morphological changes to the ACL. It is therefore unclear whether change to the MTS really leads to morphological changes in the ACL. However, previous studies have analyzed the effect of the posterior tibial slope on the biomechanics of the knee, and they support our findings [17,18]. Thus, this study may be meaningful in terms of confirming ACL changes on MRI. Second, degenerative ACL changes can occur in the normal knee as age increases. Likewise, postoperative ACL changes may be affected by the aging process, and the timing of the postoperative MRI exam was different for each patient. Although there are no significant differences in age and the time from surgery to postoperative MRI between the two groups, we cannot exclude the influence of age and time progression completely. Third, our definitions of ACL changes on MRI are confined to mucoid degeneration, the occurrence of ganglion cysts, and change in fiber shape; different definitions of ACL changes may be affected by factors different to those identified in this study. Fourth, we did not perform physical examination for ACL function. Even if morphologic changes to the ACL are detectable on MRI, it is uncertain whether these results have clinical relevance and affect patient-reported outcomes, especially in ACL function. Finally, the number of included cases was limited to those who underwent both preoperative and postoperative MRI; therefore, the sample size was relatively small (a total of 33 cases).

Despite these limitations, our study is the first to evaluate morphological changes to an uninjured ACL on MRI after OWHTO. We believe that postoperative ACL changes can be identified on MRI imaging. The present study provides evidence that some postoperative ACL changes correlate with an increase of the MTS. Further investigation of the clinical implications and a long-term serial follow-up study are needed. If the morphological changes to the ACL are related to the clinical aspect, the surgeon should pay special attention to maintaining the tibial slope.

5. Conclusion

The occurrence of morphologic ACL MRI change after OWHTO is associated with the amount of MTS change.

Disclosure of interest

The authors declare that they have no competing interest.

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No funding was received for the study.

Author's contribution

Oh-Jin Kwon: designing the study, analyzing the data, drafting and revising the manuscript.

Jong-Min Kim: designing the study, reviewing the manuscript.

Seong-Il Bin: designing the study, reviewing the manuscript.

Bum-Sik Lee: analyzing the data.

Gi-Woon Yoon: collecting the data.

Young-Hee Kwon: collecting the data.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.otsr.2019.08.005.

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