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ORIGINAL PAPER

The use of navigation in medial opening wedge high tibial osteotomy can improve tibial slope maintenance and reduce radiation exposure

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Abstract
Purposes We sought to determine the usefulness and the disadvantages of the navigation in medial opening wedge high tibial osteotomy (MOWHTO) compared to the conventional technique, in terms of target coronal alignment achievement, tibial slope maintenance, radiation exposure and operative time.
Methods We retrospectively compared 40 knees treated with navigated MOWHTO by one surgeon with 20 knees treated with conventional MOWHTO by another surgeon. Screw length of the plate was predetermined using validated simple algorithms only in the navigation group to facilitate the operation. The acceptable range of the postoperative coronal alignment was defined as 2°–6° of the mechanical tibiofemoral angle (mTFA) and 55 %–70 % of the weight loading line coordinate (WLL). The proportion of the coronal alignment outlier, posterior tibial slope change, fluoroscopy time and operative time were compared.
Results The coronal alignment outliers were fewer in the navigation group, but the differences were not significant (mTFA outlier 18 % vs. 30 %, p=0.326; WLL outlier 20 % vs. 30 %, p=0.519). Tibial slope was maintained in the navigation group (+0.3°, p=0.732), whereas increased in the conventional group (+3°, p<0.001). The fluoroscopy time was shorter in the navigation group (10.4 seconds vs. 24.8 seconds, p<0.001). The operative time was comparable in both groups (41.3 minutes vs. 39.2 minutes, p=0.232).
Conclusions The use of navigation can improve tibial slope maintenance and reduce radiation exposure in MOWHTO, without considerable extension of operative time by optimising the surgical technique.
Level of evidence Level III, retrospective comparative study.

Keywords Osteoarthritis, knee · Tibia · Osteotomy · Computer-assisted surgery · Navigation

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Introduction

High tibial osteotomy (HTO), a viable option for younger patients with medial tibiofemoral joint osteoarthritis (OA) with varus malalignment, is a load-shifting procedure that changes lower limb alignment [1]. Consequently, satisfactory outcomes after the procedure require that optimal target alignment is achieved [2]. Notably, several previous studies revealed that poorly corrected alignment was one of the most important reasons for unsatisfactory clinical results after HTO [3–5]. Given the importance of optimal target alignment to the success of HTO, opening wedge HTO has become more popular because it has a definite advantage; alignment can be adjusted during this procedure [1, 6]. Nevertheless, failure to achieve optimal target alignment has been reported for a remarkable fraction of the patients, which are frequently described as outliers [7].

Although the navigation was introduced for HTO to increase the likelihood of achieving target alignment [8, 9], the usefulness of the navigation in HTO has not yet been well established. Most of the previous studies that compared the results of navigated HTO with those after the conventional method reported that the navigated group achieved more accurate coronal alignment with less frequent outliers than the conventional group [10–16]. However, a concerning incidence of outliers is still reported even in navigated HTO, with a wide range, from 0 to 35 % [7, 10, 12, 14–17]. Whether the use of navigation improves sagittal alignment is still controversial [11–13, 18]. In addition, a theoretical advantage of the navigation is the potential to reduce radiation exposure, which has not yet been rigorously investigated [19, 20].

Similar to the experience of the use of navigation in the total knee arthroplasty, longer operative time has been suggested as a typical disadvantage of navigated HTO, owing to tracker fixation registration, compared to the conventional surgery [10, 12, 14]. The authors recently reported a novel method to estimate the length of the proximal screws of the plate, using a pre-operative plain radiograph, which has so far functioned well in our navigated medial opening wedge HTO series [21]. These simple algorithms helped us to predetermine the screw length, without the need for fluoroscopy, so we anecdotally experienced reduced fluoroscopy use and operative time. This improvement in the surgical technique is thought to be able to reduce operative time and radiation exposure.

The purpose of this study was to determine the usefulness of the navigation in medial opening wedge HTO compared to the conventional technique, in terms of target coronal alignment achievement, tibial slope maintenance and reduction of radiation exposure. We also aimed to determine whether the longer operation time, a potential disadvantage of navigated HTO, can be overcome by optimization of surgical technique, such as use of screw length-predicting algorithms which may facilitate the operation.

Patients and methods

Study design and patients allocation

This retrospective comparative study was approved by our Institutional Review Board. For this study, we defined two comparison groups: (1) the navigation group that included patients who underwent navigated HTO by a single surgeon as treatment for symptomatic varus knee OA, and (2) the conventional group that included patients who underwent conventional HTO by another surgeon for treatment of symptomatic varus knee OA. The follow-up period was more than three months. First, we reviewed 44 knees in 38 patients who underwent navigated medial opening wedge HTO in our institute from February 2012 to February 2013, in order to identify members of the navigation group. From these patients, we excluded four knees in four patients that fulfilled at least one of the following exclusion criteria: (1) patients underwent HTO to treat diseases other than primary or secondary osteoarthritis (OA), including ligament injuries (posterolateral corner injury of the knee and anterior cruciate ligament injury), developmental deformity of the knee, or for cosmetic purpose (2 knees); (2) patients whose osteotomy site were fixed with the implants other than TomoFix® (0 knee); and (3) patients whose radiographs were not adequate to measure accurate alignment due to rotation or whose radiographs were taken≥three months after surgery were not available (2 knees). Finally, 40 knees (34 patients) that underwent navigated medial opening wedge HTO for symptomatic primary varus knee OA remained. Our general indications for HTO in patients with varus knee OA were (1) moderate (Kellgren–Lawrence grade 3) radiographic medial TF OA with varus malalignment and with intact radiographic joint space at the lateral TF compartment; (2) the major component of the varus limb alignment did not stem from the distal femur but from the proximal tibia; and (3) significant and disabling pain originating from the medial side of the knee that was recalcitrant to conservative measures for>three months. There were 33 women and seven men with a mean age of 55.4 years [standard deviation (SD)=5.8, range: 43–73] and a mean body mass index (BMI) of 26.9 kg/m^2 (SD=2.6, range: 22.5–32.5) (Table 1) in this group.

To identify a conventional group with half the number of patients of the navigation group, we reviewed cases of conventional medial opening wedge HTO conducted by another surgeon in our institute in a retrograde sequential manner from May 2012, applying the same exclusion criteria as for the navigation group. Among the 33 knees in 30 patients between August 2010 and May 2012, 13 knees in 13 patients were excluded; 20 knees in 17 patients remained after the following exclusions: seven knees for diagnosis other than primary or secondary OA, three knees for other fixation device, and three for inadequate radiographs to measure alignment. There were 11 women and 9 men with a mean age of 50.0 years (SD=9.5, range: 29–60) and a mean bBMI of 25.3 kg/m^2 (SD=3.1, range: 20.0–29.8) (Table 1). Because the patients were not randomly allocated study groups, we found significant differences in all the demographic parameters except weight.

Surgical techniques

Surgical procedures for navigated HTO were controlled using information provided by the navigation system (OrthoPilot®; B. Braun Aesculap, Tuttlingen, Germany). After longitudinal skin incision on the proximal tibia, the pes anserinus was identified. Then, the superficial medial collateral ligament (MCL) was released while the pes anserinus was protected (Fig. 1a). The osteotomy site was determined by identifying

Table 1 Demographics and preoperative radiographic features of the two study groups[a]

	Navigation group (n=40)	Conventional group (n=20)	P value
Demographics			
Female[b] (%)	33 (83%)	11 (55 %)	0.032
Age (years)	55.4 (5.8)	50.0 (9.5)	0.027
Height (cm)	157.5 (7.0)	162.0 (11.0)	0.112
Weight (kg)	66.8 (8.7)	66.6 (12.4)	0.935
BMI (kg/m^2)	26.9 (2.6)	25.3 (3.1)	0.036
Diagnosis[b]			0.001
Primary osteoarthritis	40 (100 %)	14 (70 %)	
Secondary osteoarthritis	0 (0 %)	6 (30 %)	
Radiographic features			
mTFA (°)	−8.2 (2.7)	−7.1 (1.9)	0.101
WLL (%)	12.2 (10.2)	17.2 (8.0)	0.062
Tibial slope (°)	7.8 (2.9)	8.1 (3.0)	0.715

BMI body mass index, *mTFA* mechanical tibiofemoral angle, *WLL* weight loading line

[a] Results presented as mean (standard deviation)

[b] Results presented as number of patients (%)

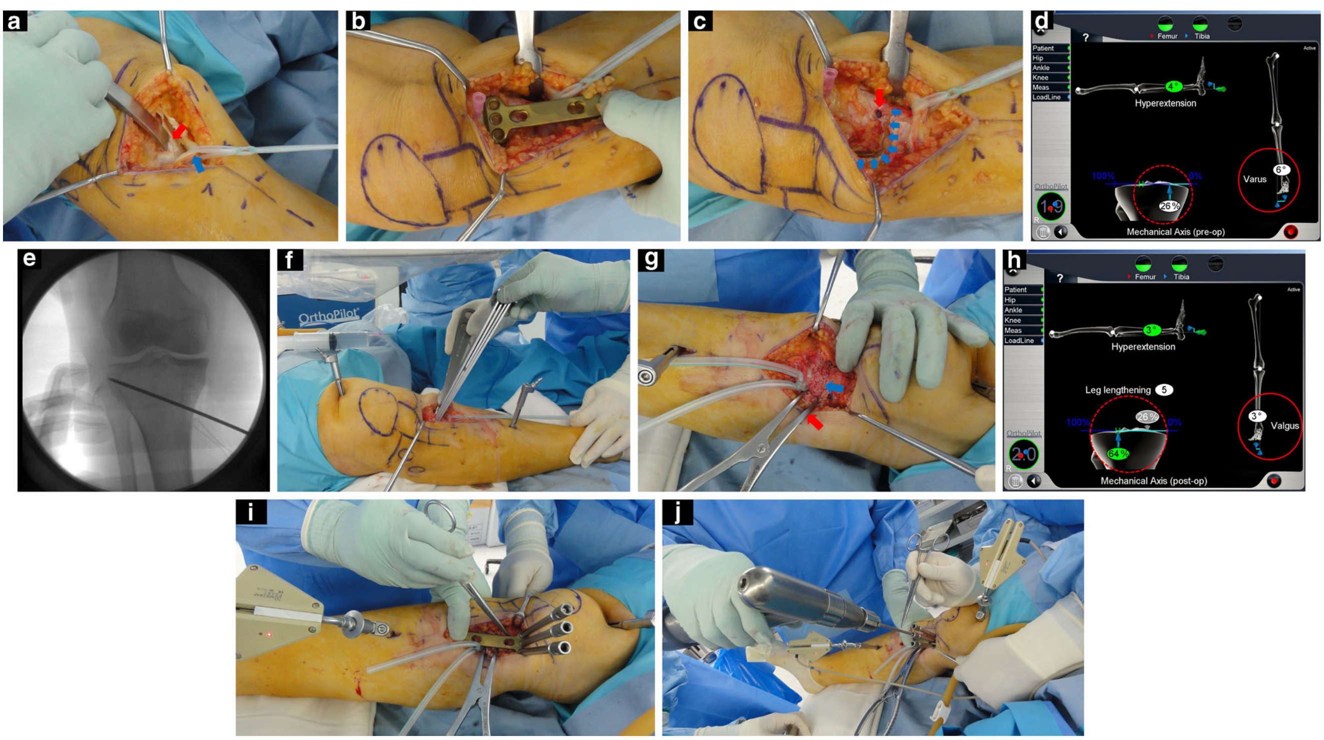

Fig. 1 The surgical technique of navigated high tibial osteotomy was presented. The superficial medial collateral ligament (MCL, *red arrow*) was released while the pes anserinus (*blue arrow*) was protected (**a**). The osteotomy site was determined by identifying the joint line using an 18-gauge syringe needle and applying a real plate (**b**). A dual osteotomy line (*blue arrows*) was drawn on the tibial surface below the position of the D screw hole (*red arrow*) (**c**). The navigation system shows the preoperative deformity in terms of mechanical tibiofemoral angle (*red circle*) and the position of the weight load line coordinate (*dotted red circle*) (**d**). Two guide pins were inserted from the determined osteotomy site with aiming the fibular tip under fluoroscopy guidance (**e**). Osteotomy was completed by stacking the four thin osteotomes after preliminary osteotomy using micro-oscillating saw (**f**). A bone spreader (*red arrow*) was used to achieve targeted correction, and the osteotomy site gap was filled with allogenous cancellous bone graft (*blue arrow*) (**g**). Achievement of targeted alignment was confirmed with the help of navigation. (**h**). While the target alignment was maintained with a bone spreader, a TomoFix® plate preloaded with three drill guides was placed at the predetermined position (**i**). Screws selected for holes A, B, C, and D using the algorithm were inserted without the use of fluoroscopy (**j**)

the joint line using an 18-gauge syringe needle and applying a real plate on the proximal tibia (Fig. 1b). A dual osteotomy line, which consisted of horizontal and vertical osteotomy, was drawn on the tibial surface below the position of D screw hole and behind the patellar tendon insertion (Fig. 1c). After femoral and tibial trackers were fixated, kinematic and anatomical registration was performed. Then, initial deformity was evaluated using the navigation system in terms of mechanical tibiofemoral angle (mTFA) and the position of the weight loading line (WLL) coordinate (Fig. 1d). Two guide pins were inserted from the determined osteotomy site, aiming the fibular tip under fluoroscopy guidance (Fig. 1e). Dual osteotomies were performed using a micro-oscillating saw system and completed with 4 thin osteotomes provided by the TomoFix® HTO system (Synthes, Solothurn, Switzerland) (Fig. 1f). Degrees of correction were determined by considering the mTFA and the position of WLL coordinate at the knee joint. The targets for the correction were a mTFA of valgus 3° and a WLL coordinate of 62 %; if both criteria were not met simultaneously, a target avoiding too much correction was chosen, typically a mTFA range of 2°–6° and a WLL coordinate range of 55 %–70 %. Allogenous cancellous bone grafts were used to fill the osteotomy sites while the corrected position was maintained with a bone spreader under navigation control (Fig. 1g, h). After gap filling of the osteotomy site, a TomoFix® plate was applied at the predetermined position (Fig. 1i). Screws selected for holes A, B, C, and D by using the simple algorithms were inserted without the use of fluoroscopy (Fig. 1j) [21]. The algorithms consisted of eight sub-algorithms, which were based on the anteroposterior (AP) length or mediolateral (ML) width measured on the pre-operative radiographs, and two algorithms for each of the four screws (Fig. 2; Table 2). If the two algorithms

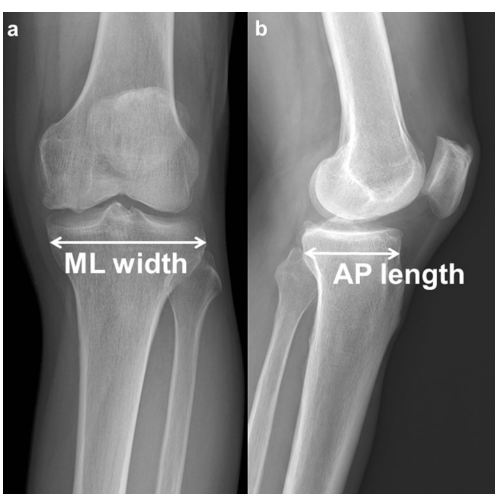

Fig. 2 Mediolateral (*ML*) width and anteroposterior (*AP*) length of the proximal tibia were measured on a parallel line 1 cm distal from the joint line identified on a standing whole-limb anteroposterior (**a**) and lateral (**b**) radiograph of the knee, respectively

Table 2 Algorithms to predict proper screw length for the four proximal screws in the TomoFix® plate

Screw hole	Proper screw length (mm)	
	Based on ML width	Based on AP length
A	ML width − 20	AP length+5
B	ML width − 25	AP length
C	ML width − 35	AP length − 10
D	ML width − 40	AP length − 15

ML mediolateral, *AP* anteroposterior

from the ML and AP dimensions suggested different lengths, a shorter screw was selected to avoid potential neurovascular complications. Once the osteotomy was completed, the procedures were controlled by navigation only and no further fluoroscopy was used except for a single exposure for a final assessment.

The conventional technique had the same targets as the navigated HTO, valgus 3° of mTFA and 62 % of the WLL coordinate. The opening gap of the osteotomy site was planned pre-operatively to determine the amount of correction. With the conventional technique, screw insertion for the TomoFix® plate was done under the control of fluoroscopy. All other surgical procedures and the rehabilitation protocols were same, irrespective of the study group.

Intra-operative measurement

During the operation, two kinds of time-related parameters were recorded, the fluoroscopy time and operative time. The fluoroscopy time was displayed on the fluoroscopy system, so the data were recorded on the case report form during every surgery. The operative time was defined as the time from the skin incision to the point that the plate was completely fixed with eight screws. It was checked by the timer in the operation room and recorded on the case report form in every surgery.

Radiographic evaluations

Radiographic evaluations were performed using double limb standing whole-leg anteroposterior radiographs and the lateral knee view; they were taken pre-operatively and postoperatively. The postoperative radiographs used in the radiographic evaluation were selected from among those obtained at≥three months after surgery; the best quality-images, without significant rotation, were selected. All the radiographs were taken on 14×51-inch grid cassettes, ensuring that the patella was facing directly anterior. All radiographic images were digitally acquired using a picture archiving communication system (PACS). Radiographic measurements were conducted on a 24-inch monitor (U2412M: Dell, Round Rock, TX, USA) in portrait mode using PACS software (Infinite, Seoul, Korea). This software could detect minimum differences of 0.1° in angle and 0.1 mm in length measurements.

To evaluate the coronal alignment, two parameters were measured; the mTFA and the WLL coordinate. The mTFA was defined as the angle formed by the intersection of the mechanical axes of the femur (the line from the femoral head centre to the femoral intercondylar notch centre) and the tibia (the line from ankle talus centre to the centre of the tibial spine tips) (Fig. 3). A negative value was assigned to the knee in varus alignment. The WLL coordinate (%) was defined as the proportion of the mechanical axis of the limb (the line from the femoral head centre to the ankle talus centre) passing through the knee from the edge of the medial tibial plateau (0 %) to the edge of the lateral tibial plateau (100 %) (Fig. 4). A negative value was assigned to severe varus with the WLL passing through the medial side of the medial edge of the tibial plateau. To evaluate the sagittal alignment, we measured the posterior tibial slope on the lateral view of the knee. This tibial slope was defined as the angle formed between the tangential line of the medial tibial plateau and the posterior cortical line connecting the two points on the posterior cortex of the tibia at 5 and 15 cm distal to the knee joint (Fig. 5) [22]. The tibial slope was expressed as the angle size minus 90°; hence, a negative slope value indicated that the angle is less than 90° and that the tibia slope is tilted anteriorly (reverse slope). The size of the changes in the tibial slope was calculated using the pre-operative and postoperative values of tibial slope, which a positive value indicated an increase in the slope after the HTO.

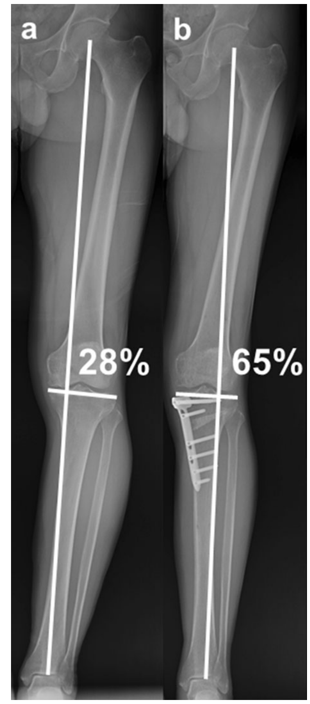

Fig. 4 Radiographs showing the pre-operative (**a**) and postoperative (**b**) weight loading line (WLL) coordinate. The WLL coordinate was defined as the proportion of the mechanical axis of the limb (the line from the femoral head centre to the ankle talus centre) passing through the knee from the edge of the medial tibial plateau (0 %) to the edge of the lateral tibial plateau (100 %)

To determine intra- and inter-observer reliabilities of radiographic assessments, two orthopedic surgeons performed radiographic assessments in 20 randomly selected knees twice within a three week interval. The intra-and inter-observer reliabilities of assessments of all radiographic measurements were evaluated using intra-class correlation coefficients

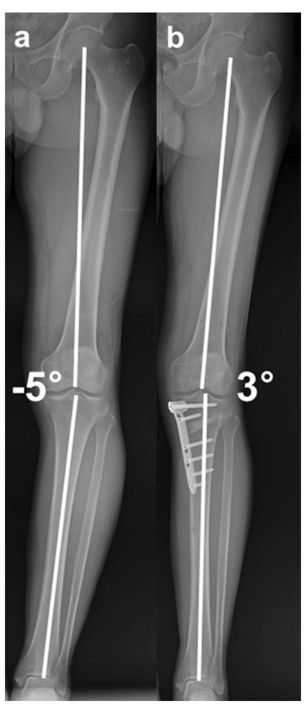

Fig. 3 Radiographs showing the pre-operative (**a**) and postoperative (**b**) mechanical tibiofemoral angle (mTFA). mTFA was defined as the angle formed by the intersection between the mechanical axes of the femur (the line from the centre of femoral head to the centre of femoral intercondylar notch) and the tibia (the line from the centre of ankle talus to the center of the tibial spine tips). A negative value was assigned to the knee in varus alignment

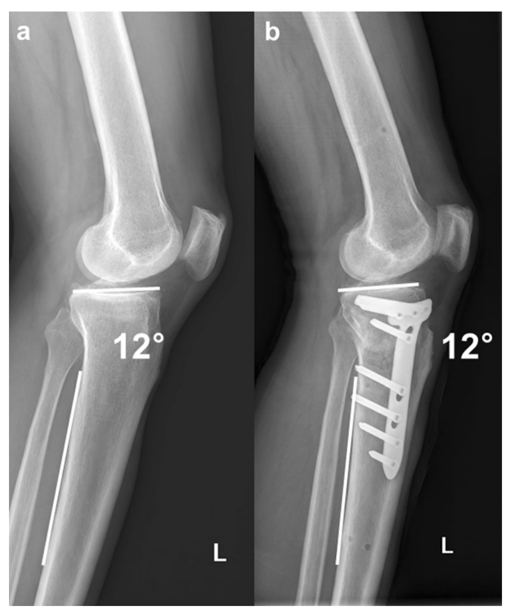

Fig. 5 Radiographs showing the pre-operative (**a**) and postoperative (**b**) tibial slope. Tibial slope was defined as the angle formed by the tangential line of the medial tibial plateau and the posterior cortical line connecting the two points on the posterior cortex of the tibia at 5 and 15 cm distal from the knee joint

(ICCs). The ICCs of intra- and inter-observer reliabilities of all measurement were> 0.9 (range: 0.902–0.994) representing satisfactory reliabilities in the measurements. Thus, measurements taken by a single investigator were used in the analyses.

Statistical analysis

All the statistical analyses were carried out with SPSS for Windows v.20.0 (IBM, Chicago, IL, USA), and p values <0.05 were considered significant. To examine differences in coronal limb alignments between the two groups, the mTFA and the WLL coordinate were compared using Student's t test. To evaluate the difference in the proportion of outliers, which were defined as the proportion of cases that deviated from the target range of valgus 2°–6° of mTFA and 55 %–70 % of WLL coordinate, we compared the two groups using the chi-square test. The preoperative and postoperative tibial slope was compared in each group using paired t test, and the amount of the changes in the tibial slope was compared between the two groups using Student's t test. The differences in the fluoroscopy time and operative time were compared between the two groups using the Student's t test.

Results

The navigation group showed better tibial slope maintenance and less radiation exposure, while the target coronal alignment achievement was not significantly improved compared to the conventional group (Table 2). The mTFA and WLL coordinate had no significant different between the navigation and conventional groups (3.5° vs. 3.3°, p=0.755 in mTFA; 64.5 % vs. 62.9 %, p=0.509 in WLL coordinate). The proportion of the coronal alignment outliers was smaller in the navigation group for both the mTFA criteria (18 % in navigation group and 30 % in conventional group, p=0.326) and the WLL coordinate criteria (20 % in navigation group and 30 % in conventional group, p=0.519). However, the differences did not reach statistical significance. The tibial slope change was not significant in the navigation group (mean change, +0.3°, p=0.732), whereas it was increased significantly in the conventional group (mean change, +3.0°, $p<0.001$). Consequently, the amount of change of the tibial slope in the conventional group was greater than the navigation group (p=0.024). The fluoroscopy time was shorter in the navigation group than the conventional group (10.4 s vs. 24.8 s, $p<0.001$).

The operative time was comparable between the two groups (Table 3). The operative time was about two minutes longer in the navigation group, but this difference was not statistically significant (41.3 minutes vs. 39.2 minutes, p= 0.232).

Discussion

Navigation was introduced in high tibial osteotomy primarily to achieve more accurate coronal alignment, which is crucial to the successful clinical outcome. However, the reported proportion of outliers in the coronal alignment after navigated HTO varied widely, and the contribution of the navigation to the control of the tibial slope control is still controversial. In addition, reduction of fluoroscopy use is a potential merit of navigated HTO, which is not well established in the literature. On the other hand, longer operative time has been a major criticism of the navigated HTO. We conducted this study to determine whether the use of navigation in HTO is advantageous, in terms of achieving target coronal alignment, maintaining tibial slope and reducing fluoroscopy use. We also aimed to determine whether the longer operation time, a potential drawback of navigated HTO, can be overcome by optimization of surgical technique, such as the use of screw length-predicting algorithms.

Our findings suggest that the use of navigation is beneficial in medial opening wedge HTO, in terms of tibial slope maintenance and reduction of radiation exposure during the surgery. There was an only minimal change in the tibial slope in the navigation group, whereas it increased by 3° in the conventional group. This finding agreed with three of the previous studies [10–12, 18], but did not agree with that of another report [13]. It has generally been accepted that the posterior tibial slope increases after medial opening wedge HTO [23–25], as we observed in our conventional group. However, we thought that the tibial slope could be maintained unchanged in the navigation group by assuring that the degree of the maximal extension remained unchanged throughout the operation using the navigational information, as described in the previous reports [10, 26]. Less radiation exposure was one of the theoretical advantages of the navigated HTO, but there is limited clinical data comparing the radiation exposure between the navigation and conventional techniques for HTO. A cadaveric study found that the fluoroscopic radiation time was shorter in the navigated HTO [19]. The fluoroscopic radiation time was 63.8 seconds in the conventional group and 53.2 seconds in the navigation group, which was considerably different from our data: 24.8 seconds and 10.4 seconds, respectively. These remarkable differences are thought to result primarily from the surgical technique and the fluoroscopy-use habit of the operators. On the other hand, 12 seconds of fluoroscopy use reported by Jackson et al. was very similar to our results [20]. Our findings confirm this theoretical advantage of navigation: fluoroscopic time was reduced to less than one-half the time of the conventional technique.

The advantage of the navigated HTO in the target coronal alignment achievement was not definitely revealed in our study. The mean values of mTFA and WLL coordinate were similar, and the occurrence of the coronal alignment outlier

Table 3 Comparison of the postoperative results of the two study groups[a]

	Navigation group (n=40)	Conventional group (n=20)	P value
mTFA (°)	3.5 (1.9)	3.3 (2.1)	0.755
Outlier (mTFA)[b] (%)	7 (18 %)	6 (30 %)	0.326
WLL coordinate (%)	64.5 (8.6)	62.9 (9.1)	0.509
Outlier (WLL)[b] (%)	8 (20 %)	6 (30 %)	0.519
Change of tibial slope[c] (°)	+0.3 (4.7), p=0.732	+3.0 (3.4), p=0.001	0.024
Fluoroscopy time (s)	10.4 (3.1)	24.8 (6.5)	<0.001
Operative time (min)	41.3 (5.6)	39.2 (4.9)	0.232

mTFA mechanical tibiofemoral angle, *WLL* weight loading line

[a] Results presented as mean (standard deviation)

[b] Results presented as number of patients (%)

[c] Positive value indicates that the tibial slope was increased after surgery compared to the preoperative status and the p values were derived from the paired t-test between the preoperative and the postoperative values within each group

was not significantly different between the two groups, although the navigation group had fewer outliers than the conventional group. Our findings were similar with several previous studies that reported fewer occurrence of coronal alignment outlier in the navigation group than the conventional method, and the proportion of the outliers was in the middle of the reported wide range (Table 4). Using power analysis, we found that a larger sample size was needed for the difference observed in our study to reach significance. Nevertheless, even with the use of navigation, 20 % of patients were outliers in our series. Although this considerable frequency of outliers may reflect the relatively narrow target range, the inherent limitation of the navigation system appears to be the major cause of outliers. Navigated surgery, which is performed with the patient supine, cannot fully reflect the standing position with full weight bearing status [27]. In addition, correction of the coronal alignment may alter the knee adduction moment, which can cause the alignment to deviate from the pre-operatively estimated result. These unpredictable factors are thought to produce discrepancies between navigational information and the alignment measured on the postoperative radiograph. Thus, further studies should be conducted to achieve improved target alignment by reducing the limitations of the current navigation-assisted surgery in HTO.

In terms of the operative time, the use of navigation did not significantly lengthen it in the current study. Our findings agreed with previous studies that reported comparable operation time in both groups [13, 15], although they conflicted with some other articles that reported longer operative times in the navigation group [10, 12, 14]. Furthermore, the additional operation time in navigation group was only about two minutes in our series, which was definitely shorter than previous studies reporting longer operation times ranging from ten to 23 minutes [10, 12, 14]. It is reasonable to predict that the navigation approach would take more time because it requires some additional steps throughout the operation compared to the conventional technique, such as tracker fixation and registration of anatomical landmarks. In our series, the simple algorithm for prior estimation of the proximal screws'

Table 4 Summary of the results of the navigated high tibial osteotomy, compared to the conventional technique in the literature

Author (Year)	No. of patients [N vs. C]	Coronal alignment outlier (%) [N vs. C]	Tibial slope maintenance	Operative time	Radiation exposure
Saragaglia (2005) [16]	28 vs. 28	4 % vs. 29 %	N/A	N/A	N/A
Maurer (2006) [14]	44 vs. 23	35 % vs. 65 %*	N/A	Longer (10 min)	N/A
Kim (2009) [13]	47 vs. 43	N/A	No difference	No difference	N/A
Bae (2009) [11]	50 vs. 50	N/A	Better	N/A	N/A
Akamatsu (2012) [10]	28 vs. 31	15 % vs. 47 %	Better	Longer (16 min)	N/A
Iorio (2013) [12]	13 vs. 11	14 % vs. 77 %	Better	Longer (23 min)	N/A
Reising (2013) [15]	40 vs. 40	0 % vs. 23 %	N/A	No difference	N/A
Ribeiro (2014) [18]	18 vs. 20	N/A	Better	N/A	N/A
The current study	40 vs. 20	18 % vs. 30 %	Better	No difference	Less

N navigation group, *C* conventional group, *N/A* not applicable

[a] Calculated from the original data of the graphs in the article

length of the TomoFix® plate was used only in the navigation group, which would eliminate the time required to check the screw length using fluoroscopy. We thought this difference in the surgical technique might have significantly affected the operative time as well the fluoroscopy time. Our findings suggest that the longer operative time, a frequently mentioned disadvantage of the navigation surgery, can be overcome by optimising the surgical procedure.

The current study has several limitations that should be considered during the interpretation of the results. First, the high tibial osteotomies in each group were performed by two different surgeons. Thus, the comparison may be affected by the surgeon factor. However, both surgeons were highly experienced in high tibial osteotomy before the start of this series, as confirmed by the results of the operative time and the target coronal alignment achievement. The operative time in the each group was far shorter than those of other reports, although we did not include about 15–20 minutes of wound closure time in the operation time [10, 13, 15]. The proportion of the coronal alignment outliers was less than those mean values of the previous studies in the literature [10, 12, 14–16]. Thus, the potential bias stemming from the surgeon effect may be limited. Second, the demographic features of the two groups were significantly different from each other, because the patients were not randomly allocated to the groups. The different patient pools of the two surgeons may explain these differences in demographic features. However, we compared accuracy of the alignment, operative time and radiation exposure, not the clinical results, such as functional status, pain or patient satisfaction, outcomes that can be confounded by demographic characteristics. Thus, we believe that the differences in the demographics did not considerably limit the validity of this study. Third, the prior screw length estimation algorithm was used only in the navigation group. This might have distorted parallel comparisons of the fluoroscopy and operative times, but not in the radiologic outcome, between the navigated and conventional HTO groups. However, longer operation time was already reported as a disadvantage of navigated HTO so we did not expect that the navigated HTO could be performed in shorter operation times than conventional HTO [10, 12, 14]. Rather, we wanted to know whether the longer operative time of the navigation surgery could be overcome by improving the surgical procedure, such as the use of our algorithms to predict screw length of the plate. Finally, we did not compare functional outcome owing to the short-term follow-up period. Thus, further study is required to reveal whether there will be differences in the clinical outcome after navigated HTO compared to the conventional technique.

In conclusion, the use of navigation in the medial opening wedge HTO is beneficial for the maintenance of tibial slope and reduction of the radiation exposure when compared to the conventional technique. The longer operation time, a typical potential disadvantage of navigation, can be overcome by optimizing the surgical procedure. Therefore, we recommend the use of navigation in the medial opening wedge HTO, for more precise sagittal alignment control and radiation safety of the patients and the surgeons, without considerable extension of operative time.

Acknowledgments Each author certifies that his or her institution has approved the human protocol for this investigation, and that all investigations were conducted in conformity with ethical principles of research, and that informed consent was obtained. This work was performed at the Joint Reconstruction Center, Seoul National University Bundang Hospital.

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