



Original Article

Comparison of a patient-specific instrument and conventional high tibial Osteotomy: Accuracy of correction target and prevention of posterior tibial slope change

Joo Hyung Han^a, Min Jung^{b,c}, Kwangho Chung^{b,d}, Sungjun Kim^e, Min Ho Lee^f,
Chong-Hyuk Choi^{b,c}, Sung-Hwan Kim^{b,f,*}^a Yonsei University College of Medicine, Seoul, Republic of Korea^b Arthroscopy and Joint Research Institute, Yonsei University College of Medicine, Seoul, Republic of Korea^c Severance Hospital, Yonsei University College of Medicine, Seoul, Republic of Korea^d Yongin Severance Hospital, Yonsei University College of Medicine, Yongin, Republic of Korea^e Department of Radiology, Gangnam Severance Hospital, Yonsei University College of Medicine, Seoul, Republic of Korea^f Department of Orthopedic Surgery, Gangnam Severance Hospital, Yonsei University College of Medicine, Seoul, Republic of Korea

ARTICLE INFO

Keywords:

Accuracy

high tibial osteotomy

knee

patient-specific Instrument

tibial slope

ABSTRACT

Background: High tibial osteotomy (HTO) is crucial for managing medial compartmental knee osteoarthritis. Precision in achieving the medial proximal tibial angle (MPTA) correction and maintenance of posterior tibial slope (PTS) is essential for clinical success. This study aims to compare the use of 3D-printed patient-specific instruments (PSI) to conventional HTO to achieve precise MPTA correction and maintenance of PTS, aiming to enhance surgical outcomes in HTO patients.

Methods: Among 104 patients who underwent HTO between September 2018 and July 2021, 60 met the inclusion criteria and were categorized into a PSI group (30 cases) and conventional method group (30 cases). Radiological outcomes included estimated and postoperative MPTA values, along with preoperative and postoperative PTS measurements.

Results: Within the conventional HTO group, significant differences were noted between the estimated and postoperative MPTA values ($94.3^\circ \pm 2.4^\circ$ vs. $93.5^\circ \pm 2.5^\circ$, $P = 0.023$), as well as between the preoperative and postoperative PTS values ($8.8^\circ \pm 3.2^\circ$ vs. $7.9^\circ \pm 3.5^\circ$, $P = 0.033$). Conversely, the PSI group did not exhibit any significant differences in these values.

Conclusion: This study indicated that the use of PSI-guided HTO could provide enhanced accuracy in achieving the target MPTA and improve the prevention of PTS changes.

1. Introduction

High tibial osteotomy (HTO) aims to redistribute the load-bearing axis to relieve pain and improve clinical outcomes in medial compartment osteoarthritis.^{1–4} Accurate correction is critical, as both under-correction and overcorrection are major causes of clinical failure.^{5–7} The medial proximal tibial angle (MPTA), with a normal value of approximately 87° , is commonly used to assess correction accuracy.^{8,9} Posterior tibial slope (PTS) is also a key factor, as unintended changes during medial open-wedge HTO—such as from incomplete posterior corticotomy or anterior fixation plate positioning—may result in knee

instability and increased stress on the cruciate ligaments.^{10,11}

The demand for accuracy in the planning and execution of HTO may be addressed by the emergence of a novel ancillary technology known as 3D-printed patient-specific instrumentation (PSI).^{12,13} Recent systematic reviews have evaluated the utility of PSI in medial opening-wedge HTO. Dasari et al.¹⁴ concluded that PSI achieves high accuracy in coronal, sagittal, and mechanical axis corrections, with a low risk of major complications. Conversely, Pang et al.¹⁵ reported that although PSI is accurate, it may not be essential for typical HTO cases. These findings underscore ongoing debate regarding the clinical necessity of PSI, warranting further investigation into its practical benefits and

* Corresponding author. Gangnam Severance Hospital, Yonsei University College of Medicine, 211 Eonju-ro, Gangnam-gu, Seoul, 130-729, Republic of Korea.

E-mail addresses: hanjh93@gmail.com (J.H. Han), jmin1103@yuhs.ac (M. Jung), khchung85@yuhs.ac (K. Chung), agn70@yuhs.ac (S. Kim), mhlee164@naver.com (M.H. Lee), CHOI8422@yuhs.ac (C.-H. Choi), orthohwan@gmail.com (S.-H. Kim).

<https://doi.org/10.1016/j.asmart.2025.08.006>

Received 29 November 2024; Received in revised form 23 April 2025; Accepted 4 August 2025

2214-6873/© 2025 Asia Pacific Knee, Arthroscopy and Sports Medicine Society. Published by Elsevier (Singapore) Pte Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

limitations.

The purpose of this study was to analyze and compare the effectiveness of 3D-printed PSI and conventional HTO in achieving the target angle during surgical correction. This was accomplished by evaluating changes in MPTA and PTS resulting from each technique. By comparing these outcomes, we aimed to assess the accuracy and precision of PSI-guided HTO in comparison with the conventional approach. The findings of this study would provide valuable insights into the advantages and limitations of the PSI technology in improving surgical outcomes in patients undergoing HTO.

2. Materials and methods

2.1. Patients

A retrospective review of 107 patients who underwent HTO at a single tertiary center between September 2018 and July 2021 was conducted. All experimental protocols in this study were approved by the institutional review board of the participating institution to ensure compliance with ethical and research standards (IRB 3-2023-0270). Informed consent was obtained from all subjects participating in the study, and in cases involving minors or individuals lacking capacity, informed consent was also acquired from their legal guardian(s) in accordance with established ethical guidelines.

The inclusion criteria for HTO were individuals aged under 60 years with varus alignment who were diagnosed with symptomatic medial compartment osteoarthritis. Additionally, eligible patients were required to have a range of motion with flexion $\geq 120^\circ$ and extension loss $\leq 10^\circ$. Only those who had not responded to conservative treatments—including oral medications and intra-articular injections—for more than 3 months were considered for HTO as a treatment option. The exclusion criteria included notable patellofemoral symptoms, lateral tibiofemoral joint arthritis, and a history of prior knee surgery with existing hardware. In addition, individuals without appropriate preoperative and postoperative radiographic images were excluded from the study.

A total of 104 patients were included in the study, with 51 and 53 patients in the PSI and conventional HTO groups, respectively. The allocation of patients to either group was not randomized but was determined chronologically based on the surgical period. Conventional HTO was performed during the earlier phase of the study, while PSI HTO was conducted later, following the implementation of patient-specific instrumentation at our institution. To minimize potential confounding

and improve comparability between groups, propensity score matching was conducted based on age, sex, body mass index (BMI), correction angle, preoperative hip-knee-ankle angle (HKA), and International Cartilage Repair Society (ICRS) grade. Following propensity score matching, a final cohort of 60 patients was included in the analysis, with 30 patients in each group. A flow diagram of this study is presented in Fig. 1.

2.2. Preoperative planning

A comprehensive range of imaging techniques was utilized for preoperative planning, encompassing standard weight-bearing knee radiographs, standing long leg radiographs, and computed tomography (CT) scans of the lower extremities (SOMATOM Force, Siemens Healthineers, Erlangen, Germany). CT imaging was selected because of its high-resolution capabilities, allowing precise segmentation of the bones and facilitating detailed preoperative planning for PSI.

Bone models were extracted semi-automatically from the CT scans using the segmentation functionality of Mimics software (Materialize, Leuven, Belgium). This process involved the generation of 3D triangular surface models of the relevant anatomical structures, as described in a previous study.¹⁶ A computerized osteotomy simulation software was used to create virtual 3D models of the bone anatomy of the lower limb.

Once the optimal sagittal and coronal correction angles and osteotomy position were determined, a PSI cutting guide model (Skyve R&D LAB, Seoul, Republic of Korea) was built using additive layer manufacturing (3D printing) to ensure a precise osteotomy. The prepared PSI was stored in an ethylene oxide gas-sterilized condition prior to surgery.

Preoperative planning in the conventional group was performed using the Miniaci method on full-length weight-bearing radiographs to determine the correction angle and opening gap required for proper realignment.

2.3. Surgical procedures

Under general anesthesia, the patients were placed in a supine position on the operating table. A pneumatic tourniquet was applied to the right upper thigh and set at 320 mm Hg. Following the usual sterile orthopedic protocol for skin preparation and draping, the pneumatic tourniquet was inflated. Initially, intra-articular procedures were conducted, including arthroscopy to investigate concurrent conditions, as well as for articular debridement, removal of loose bodies, and

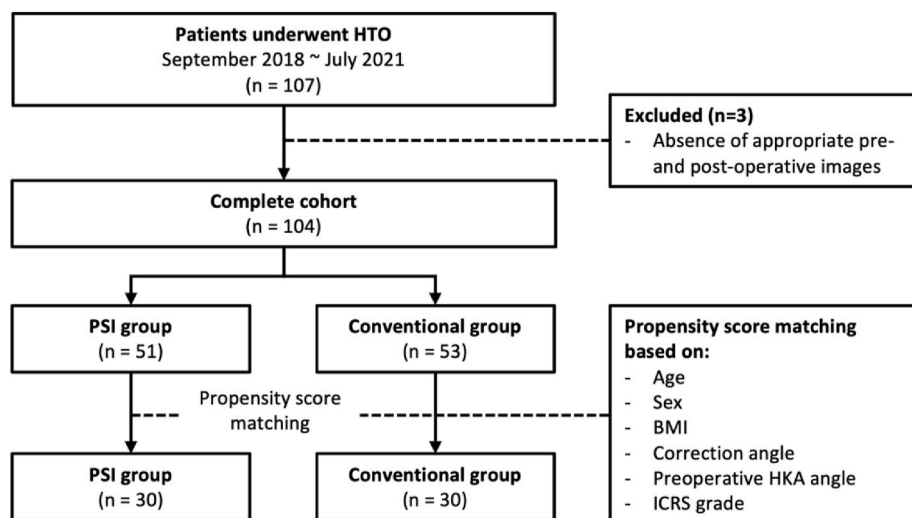


Fig. 1. Flow diagram illustrating the patient selection and matching process. HTO, high tibial osteotomy; K-L, Kellgren-Lawrence; OA, osteoarthritis; ROM, range of motion; PSI, patient specific instrument; BMI, body mass index; HKA, hip-knee-ankle; ICRS, International Cartilage Repair Society.

meniscectomy. Subsequently, an oblique skin incision approximately 7 cm in length was made, starting from the upper aspect of the insertion site of the pes anserinus. Dissection was performed to expose the medial collateral ligament, and the distal attachments were released.

Using a C-arm image intensifier (Arcadis Varic, Siemens Healthineers, Erlangen, Germany) for anteroposterior view confirmation, a guide pin was inserted into the medial cortex of the tibia and directed towards the fibular head. Another guide pin was inserted in the same manner, anteriorly and parallel to the first pin. After partially cutting the tibia at the distal margin of the guide pins, osteotomy was performed using an electric saw parallel to the guide pins. Open-wedge osteotomy was then performed by sequentially inserting a wide osteotome blade into the osteotomy site. The 3D PSI used in the surgery played the role of a spacer. After the osteotomy, the PSI was inserted into the corresponding site, aligning the tibial cortex with the margin of the PSI, ensuring that the gap at the osteotomy site was maintained according to the pre-designed angles (Fig. 2). Subsequently, fixation was performed using a TomoFix plate (DePuy Synthes, Oberdorf, Switzerland) and locking screws. Afterward, the PSI was removed, and allogeneic cancellous bone chips were grafted into the open-wedge space in cases requiring a correction angle of 10 degrees or more.

In the conventional HTO group, the osteotomy sites were visually determined with the assistance of intraoperative C-arm fluoroscopy. Two-plane osteotomy was then performed accordingly. Correction angle, hardware positioning, and accuracy were repeatedly assessed using a C-arm fluoroscope. Subsequently, plate fixation and allogeneic bone grafting were performed in the same manner.

One Hemovac drain was inserted intraarticularly, and another drain was inserted at the osteotomy site. The wound was sutured in layers, and after applying an aseptic dressing, anti-embolic stockings were applied. Subsequently, the patient was transferred to the recovery room.

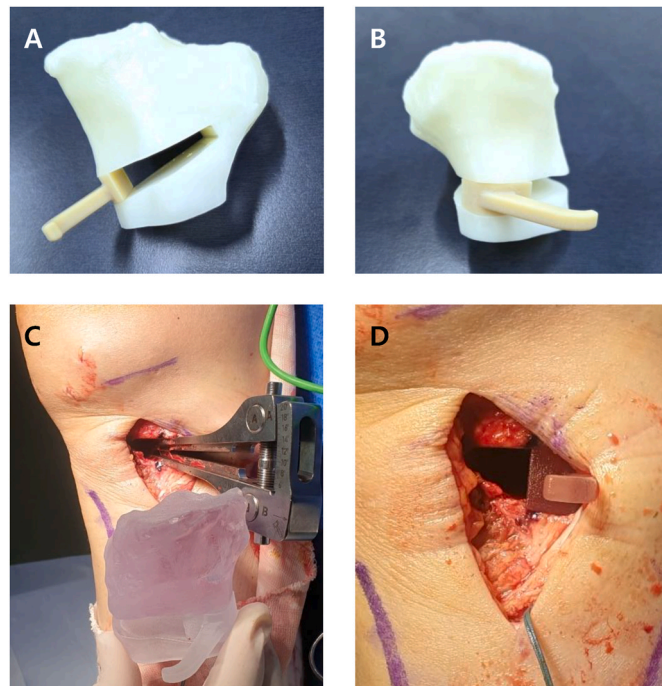


Fig. 2. (A, B) Anterior and lateral views of the 3D bone model with the attached patient-specific instrument (PSI). (C) Open-wedge osteotomy performed following the initial osteotomy using an electric saw. (D) Sequential insertion of a wide osteotome blade into the osteotomy site, guided by the pre-designed 3D patient-specific instrument.

2.4. Radiological outcomes

Two-dimensional (2D) images were obtained using the Picture Archiving and Communication System (GE Healthcare, Chicago, IL, USA). MPTA was measured on standing lower-extremity radiographs and was determined as the angle formed by the mechanical axis of the tibia and tangent line of the tibial plateau. PTS was measured on full-length tibial lateral-view radiographs and was assessed as the angle between a line perpendicular to the mechanical axis of the tibia and an average line connecting the medial and lateral tibial plateaus.¹⁷

For MPTA, the estimated and postoperative values were measured. Estimated MPTA was defined as the MPTA obtained by drawing a virtual osteotomy line on preoperative standing lower-extremity radiographs and rotating the distal part of the image by the correction angle used in the HTO. Postoperative MPTA measurements were obtained 3 months after surgery. For PTS, preoperative and postoperative values were measured. PTS measurements were obtained using radiographic imaging 6 weeks postoperatively (Fig. 3).

The accuracy of 2D measurements was assessed using two variables. Δ MPTA represented the difference between the postoperative and estimated MPTA. A positive value indicated overcorrection, whereas a negative value indicated undercorrection. Similarly, Δ PTS was calculated by subtracting preoperative PTS from postoperative PTS. A positive value indicated a steeper slope than the preoperative slope. These values were analyzed to quantitatively compare the magnitudes and trends of the errors associated with each method. The measurements were repeated at 2-week intervals by two different orthopedic surgeons, who were blinded to whether the surgery was conventional HTO or PSI-guided, to ensure reliability.

2.5. Statistical analysis

Statistical analyses were conducted using appropriate methods in this study. For categorical data, the chi-square test was used to assess the significance of differences between the groups. Continuous data were analyzed using the *t*-test to evaluate statistically significant variations. A *P*-value less than 0.05 was considered indicative of statistical significance. Intraclass correlation coefficients (ICC) were calculated to evaluate interrater reliability. ICC values were used to assess the consistency and agreement between the raters. All statistical analyses were performed using the R software (version 4.2.1; R Foundation, Vienna, Austria), and data visualization was performed using the ggplot2 package (v3.4.2; Wickham, 2016).

3. Results

Baseline characteristics of the two groups are summarized in Table 1. After propensity score matching, no significant differences were observed between the PSI and conventional HTO groups in age, sex distribution, BMI, preoperative HKA angle, or ICRS grade of the medial femoral condyle. No significant differences were found in the preoperative MPTA or PTS between the two groups ($P = 0.876$ and $P = 0.777$, respectively; Table 2).

In the conventional group, the estimated MPTA was $94.3^\circ \pm 2.4^\circ$, whereas the postoperative MPTA was $93.5^\circ \pm 2.5^\circ$. The postoperative MPTA was significantly lower than the estimated MPTA ($P = 0.023$). In the PSI group, the estimated MPTA was $94.1^\circ \pm 2.6^\circ$ and the postoperative MPTA was $94.4^\circ \pm 2.3^\circ$, with no significant difference observed between the two values ($P = 0.468$). No significant differences in the estimated or postoperative MPTA values were observed between the two groups ($P = 0.695$ and $P = 0.144$, respectively; Fig. 4).

In the conventional HTO group, the preoperative PTS was $8.8^\circ \pm 3.2^\circ$, whereas the postoperative PTS was $7.9^\circ \pm 3.5^\circ$. The postoperative PTS was significantly lower than the preoperative PTS ($P = 0.033$). In the PSI group, the preoperative PTS was $9.0^\circ \pm 3.0^\circ$ and the postoperative PTS was $8.5^\circ \pm 2.5^\circ$, with no significant difference between

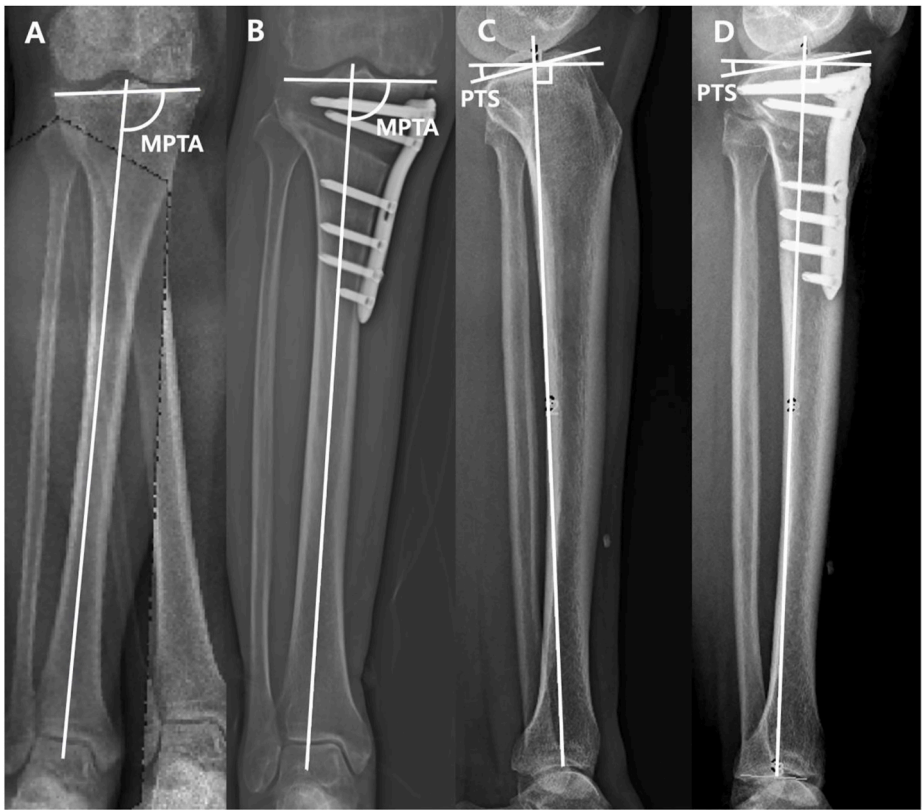


Fig. 3. MPTA (A and B) is determined by measuring the angle formed between the mechanical axis of the tibia and tangent line of the tibial plateau. To estimate the preoperative MPTA (A), a virtual osteotomy line is drawn on the preoperative radiographs, and the distal part of the image is rotated by the correction angle used in the high tibial osteotomy. Postoperative MPTA (B) measurements have been taken 3 months after the surgery. PTS (C and D) is assessed as the angle between a perpendicular line to the mechanical axis of the tibia and an average line connecting the medial and lateral tibial plateaus. Preoperative PTS (C) measurements have been obtained before the surgery, whereas postoperative PTS (D) measurements have been taken 6 weeks after the surgery. MPTA, medial proximal tibial angle; PTS, posterior tibial slope.

Table 1
Summary of the demographic characteristics of the patients in the PCI and conventional groups.

Variables	PSI group (n = 30) (mean ± SD)	Conventional group (n = 30) (mean ± SD)	P-value
Age, y	57.5 ± 5.6	57.6 ± 8.7	0.958
Sex, n (%)			>0.999
Male	7 (23.33 %)	7 (23.33 %)	
Female	23 (76.67 %)	23 (76.67 %)	
BMI, kg/m2	25.9 ± 2.5	26.2 ± 4.2	0.847
Preoperative HKA	6.73 ± 2.54	6.95 ± 2.67	0.7824
ICRS grade (MFC), n (%)			0.781
3	9 (30.00 %)	10 (33.33 %)	
4	21 (70.00 %)	20 (66.67 %)	

PSI, patient-specific instrument; SD, standard deviation; BMI, body mass index, HKA, hip-knee-ankle, ICRS, International Cartilage Repair Society; MFC, medial femoral condyle.

the two values ($P = 0.299$). No significant differences in the preoperative and postoperative PTS values were observed between the two groups ($P = 0.777$ and $P = 0.430$, respectively; Fig. 5).

In the conventional HTO group, the Δ MPTA was $-0.9^\circ \pm 2.0^\circ$, whereas in the PSI group, it was $0.3^\circ \pm 2.2^\circ$. A significant difference was observed in the Δ MPTA values between the conventional HTO and PSI groups ($P = 0.034$). The Δ PTS was $-0.9^\circ \pm 2.3^\circ$ in the conventional HTO group and $-0.5^\circ \pm 2.7^\circ$ in the PSI group, with no significant difference between the groups ($P = 0.537$, Fig. 6, Table 2).

Intra-observer and inter-observer reliabilities for MPTA

Table 2
Estimated and postoperative MPTA, preoperative and postoperative PTS, and calculated Δ MPTA and Δ PTS values in the PSI and conventional groups.

Variables	Conventional group (mean ± SD)	PSI group (mean ± SD)	P-value
Preoperative MPTA	84.6° ± 2.2°	84.5° ± 2.5°	0.876
Estimated MPTA	94.3° ± 2.4°	94.1° ± 2.6°	0.695
Postoperative MPTA	93.5° ± 2.5°	94.4° ± 2.3°	0.144
P-value	0.023*	0.468	
Preoperative PTS	8.8° ± 3.2°	9.0° ± 3.0°	0.777
Postoperative PTS	7.9° ± 3.5°	8.5° ± 2.5°	0.430
P-value	0.033*	0.299	
ΔMPTA	$-0.9^\circ \pm 2.0^\circ$	$0.3^\circ \pm 2.2^\circ$	0.034*
ΔPTS	$-0.9^\circ \pm 2.3^\circ$	$-0.5^\circ \pm 2.7^\circ$	0.537

MPTA, medial proximal tibial angle; PTS, posterior tibial slope; SD, standard deviation, *: <0.05.

measurements were excellent, with ICCs of 0.96 and 0.93, respectively. For PTS measurements, intra-observer ICC was 0.94 and the inter-observer ICC was 0.91.

During the follow-up period, no complications such as surgical site infection, neurovascular injury, delayed bone healing, or implant-related issues were observed in either the conventional or PSI HTO groups. Consequently, there were no differences in complication rates between the two groups.

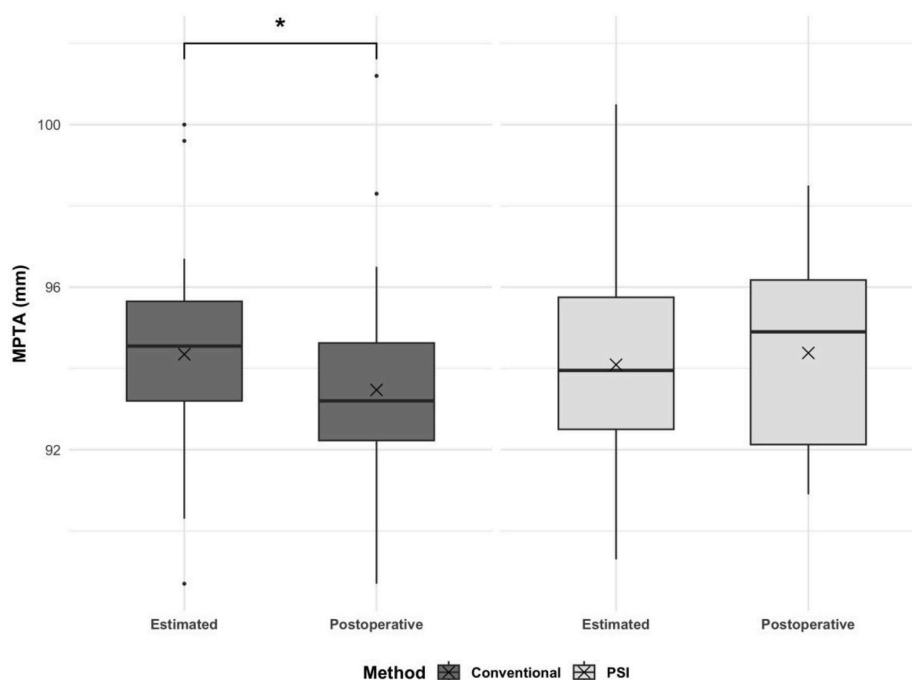


Fig. 4. Box plot of estimated and postoperative MPTA for each group. The postoperative MPTA is significantly smaller than the estimated MPTA ($P = 0.023$) in the conventional HTO group. No significant difference is observed between the two values ($P = 0.4679$) in the PSI group. No significant differences in the estimated and postoperative MPTA values are noted between the two groups ($P = 0.6945$, $P = 0.1438$). MPTA, medial proximal tibial angle; PSI, patient-specific instrument; *: $P < 0.05$.

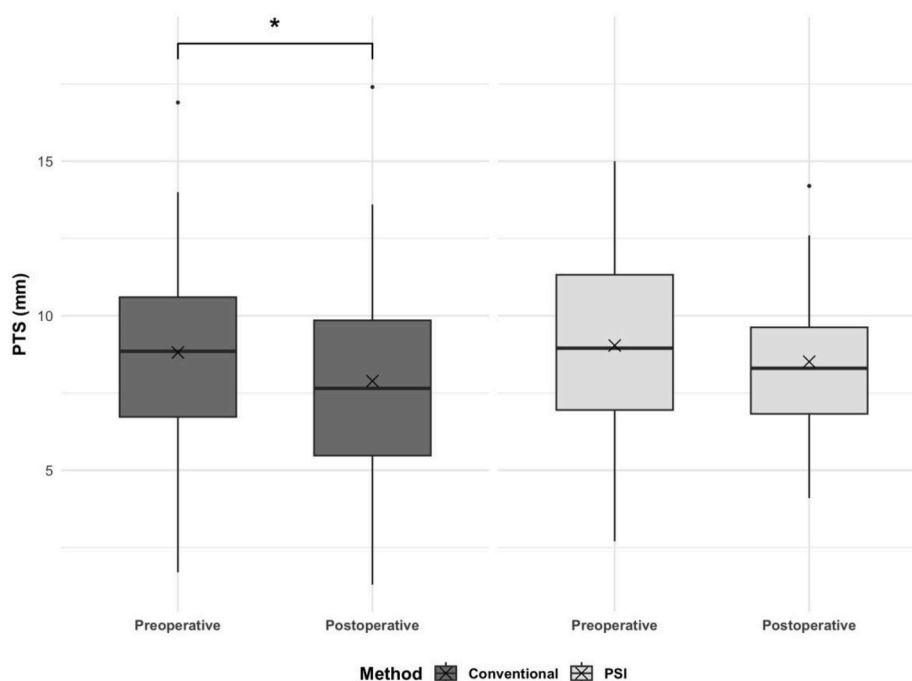


Fig. 5. Box plot of preoperative and postoperative PTS for each group. The postoperative PTS is significantly smaller than the preoperative PTS ($P = 0.0325$) in the conventional HTO group. No significant difference is observed between the two values ($P = 0.2999$) in the PSI group. No significant differences in the estimated and postoperative PTS values are noted between the two groups ($P = 0.777$, $P = 0.4302$). PTS, posterior tibial slope; PSI, patient-specific instrument; *: $P < 0.05$.

4. Discussion

The key finding of this study is that PSI-guided HTO demonstrated significantly greater accuracy in achieving the planned correction angle than conventional HTO. Specifically, the postoperative MPTA in the conventional group was significantly smaller than the estimated MPTA

($P = 0.023$), whereas no significant difference was observed in the PSI group ($P = 0.468$). Moreover, the Δ MPTA was significantly lower in the PSI group ($P = 0.034$), indicating a reduced tendency for under-correction. Given that inaccurate correction is a well-established risk factor for clinical failure in HTO,⁵ the improved precision observed with PSI suggests that its use may enhance surgical outcomes by optimizing

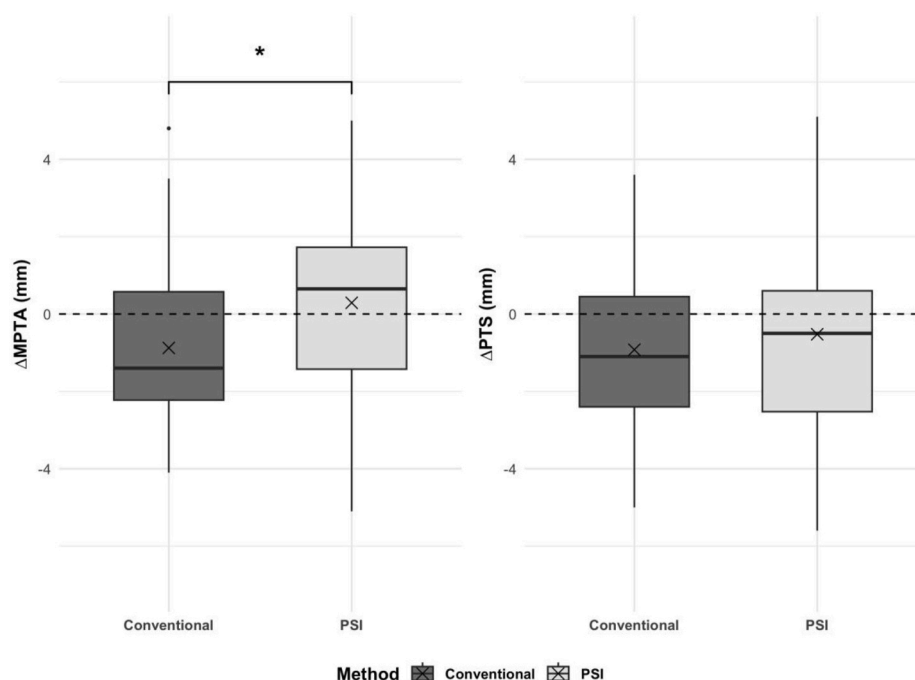


Fig. 6. Box plot of Δ MPTA and Δ PTS for each group. A significant difference is observed in the Δ MPTA values between the conventional HTO and PSI groups ($P = 0.0344$). No significant differences in the Δ PTS values are noted between the conventional HTO and PSI groups ($P = 0.5371$). MPTA, medial proximal tibial angle; PTS, posterior tibial slope; PSI, patient-specific instrument; *: $P < 0.05$.

alignment correction.

In terms of PTS, in the conventional HTO group, the postoperative PTS was significantly smaller than the preoperative value ($P = 0.033$), whereas no significant difference was observed between the preoperative and postoperative values in the PSI group ($P = 0.299$). Although no statistically significant difference in Δ PTS was observed between the two groups ($P = 0.537$), the conventional HTO group exhibited a notable trend of decreasing PTS. The disparity is possibly attributable to the surgical technique used by the surgeon to prevent an increase in PTS. Various methods have been proposed, such as maintaining an anterior gap and posterior gap ratio of approximately 67–70 % during osteotomy in the surgical process of medial open-wedge HTO, to preserve PTS.¹⁸

Generally, it is known that PTS can increase in medial open-wedge HTO due to factors such as incomplete posterior corticotomy, anterior positioning of the fixation plate, intraoperative technique, and plate design.^{19–21} Among these, the intraoperative technique is considered one of the most technically demanding aspects, particularly for less experienced surgeons. The use of PSI addresses these technique-related challenges by guiding accurate osteotomy and plate positioning, thereby helping maintain the intended PTS. Thus, PSI serves as a valuable tool for preserving PTS and improving surgical consistency, especially for novice surgeons.

Several studies have evaluated the accuracy of PSI. In our study, the error in MPTA was determined to be $0.3^\circ \pm 2.2^\circ$, which is consistent with the errors of 0.5° – 0.8° reported in other studies.^{22,23} Similarly, the error in the PTS group was observed to be $0.5^\circ \pm 2.7^\circ$, showing a comparable level of error to the values of approximately 0.4° – 1.7° reported in previous studies.^{22–24} However, although the absolute angle differences in the conventional group in our study were not significantly large, their potential clinical impact should not be overlooked. To minimize measurement bias, the measurements were repeated with intervals by two different orthopedic surgeons who were blinded to whether the surgery was conventional HTO or PSI-guided to ensure reliability, although the influence of this process cannot be entirely excluded. Ultimately, considering the role of HTO in delaying the need for additional surgeries, such as arthroplasty, a patient's clinical

symptoms appear to be the most crucial factor when determining treatment. Therefore, further studies on long-term clinical outcomes are needed to determine the true clinical significance.

Previous studies have explored the clinical utility of PSI in HTO with varying conclusions. For instance, Tardy et al.²⁵ found no significant superiority of PSI over conventional or navigated techniques, concluding that all three methods were comparably reliable and precise in achieving planned corrections. In contrast, a systematic review by Dasari et al.¹⁴ reported that PSI yields high accuracy across coronal, sagittal, and mechanical axes, with a low risk of major complications. Similarly, Pang et al.¹⁵ confirmed the accuracy of PSI in their meta-analysis but questioned its necessity in typical HTO cases. These differing results may be attributed to variations in surgical protocols, imaging modalities, and PSI design across studies. In our study, PSI was designed using standard CT imaging and applied with meticulous intraoperative referencing, which may have contributed to the favorable accuracy outcomes observed.

This study demonstrated that PSI had promising outcomes in terms of achieving an accurate target MPTA and maintaining PTS. The advantages of using PSI-guided HTO include shorter operating times, a shorter learning curve, reduced fluoroscopy time, the ability to perform concomitant procedures, and enhanced recovery after surgery.^{22,26} However, it should be noted that the PSI used in this study is not yet a commercially available product. Therefore, when it becomes more widely accessible, additional considerations should be given to the potential financial burden on patients and the efforts involved in the manufacturing process. Nevertheless, considering the aforementioned advantages, there is a strong rationale for further promoting the utilization of PSI-guided HTO.

This study had several limitations. First, the study had a retrospective design. Second, the sample size was relatively small, which may have limited the generalizability of the study's findings. Third, patients were not randomized to the conventional or PSI group; instead, allocation was determined chronologically based on the timing of surgery, with conventional HTO performed during the earlier phase and PSI HTO during the later phase following the implementation of 3D printing at

our institution. Although efforts were made to minimize selection bias through propensity score matching, residual confounding related to the non-randomized, time-based group allocation may still exist. Additionally, PSI was developed using 3D CT images; however, this study relied on 2D radiographic images for analysis. Therefore, the potential benefits and accuracy of PSI may not have been fully captured in this study. Moreover, conducting further analysis based on postoperative CT images would provide a more comprehensive evaluation of the operative outcomes. Lastly, patient-reported outcome scores were not included due to inconsistent documentation over the long-term follow-up, and data on fluoroscopy time and surgery duration were not collected. These factors are important for assessing the efficiency and safety of PSI-guided HTO, and future studies should incorporate them. These limitations underscore the need for larger, prospective studies with advanced imaging, standardized clinical assessments, and a focus on time-related outcomes to validate our findings.

In conclusion, the findings of this study indicated that the use of PSI-guided HTO could provide enhanced accuracy in achieving the target MPTA and preventing PTS changes. These results highlighted the potential benefits of incorporating the PSI technology into HTO procedures, contributing to improved surgical precision and patient outcomes.

Ethics approval and consent to participate

This study was ethically approved by the institutional review board (3-2023-0270). Consent not applicable due to the retrospective nature of the study.

Consent for publication

Not applicable due to the retrospective nature of the study.

Availability of data and material

The datasets during and/or analyzed during the current study available from the corresponding author on reasonable request.

Authors' contributions

SHK conceived and designed the study. JHH, MHL, and SK acquired the data. Data analysis and interpretation were performed by JHH, MJ, CHC, and KC. JHH and MHL drafted the manuscript. MJ, KC, SK, CHC, and SHK critically revised the manuscript for important intellectual content. All authors read and approved the final version of the manuscript.

Funding/support statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest statement

The authors declare that they have no conflicts of interest relevant to this study.

Acknowledgements

Not applicable.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.asmart.2025.08.006>.

References

- Yang HY, Yoon TW, Kim JY, Seon JK. Radiologic assessment of knee phenotypes based on the coronal plane alignment of the knee classification in a Korean population. *Clin Orthop Surg*. Jun 2024;16(3):422–429. <https://doi.org/10.4055/cios23250>.
- Constantin H, Salmon LJ, Russell V, Sundaraj K, Roe JP, Pinczewski LA. 20-Year outcomes of high tibial osteotomy: determinants of survival and functional outcome. *Am J Sports Med*. Feb 2024;52(2):344–351. <https://doi.org/10.1177/03635465231217742>.
- Lim CW, Ryu DJ, Suh YJ. Association between low serum creatinine levels and knee osteoarthritis in Koreans without renal insufficiency. *Yonsei Med J*. Sep 2024;65(9):519–526. <https://doi.org/10.3349/ymj.2023.0456>.
- Yoon HK, Park SH, Oh HC, Ha JW, Choi H. Combined PCL and PLC reconstruction improves residual laxity in PCL injury patients with posterolateral knee laxity less than grade III. *Yonsei Med J*. May 2023;64(5):313–319. <https://doi.org/10.3349/ymj.2022.0487>.
- Brinkman JM, Lobenhoffer P, Agneskirchner JD, Staubli AE, Wymenga AB, van Heerwaarden RJ. Osteotomies around the knee: patient selection, stability of fixation and bone healing in high tibial osteotomies. *J Bone Joint Surg Br*. Dec 2008;90(12):1548–1557. <https://doi.org/10.1302/0301-620x.90b12.21198>.
- Kang BY, Lee DK, Kim HS, Wang JH. How to achieve an optimal alignment in medial opening wedge high tibial osteotomy? *Knee Surg Relat Res*. Feb 8 2022;34(1):3. <https://doi.org/10.1186/s43019-021-00130-2>.
- Han JH, Jung M, Chung K, Jung SH, Choi CH, Kim SH. Effects of concurrent cartilage procedures on cartilage regeneration in high tibial osteotomy: a systematic review. *Knee Surg Relat Res*. Mar 28 2024;36(1):13. <https://doi.org/10.1186/s43019-024-00221-w>.
- Mullaji A, Shah R, Bhoskar R, Singh A, Haidermota M, Thakur H. Seven phenotypes of varus osteoarthritic knees can be identified in the coronal plane. *Knee Surg Sports Traumatol Arthrosc*. Aug 2022;30(8):2793–2805. <https://doi.org/10.1007/s00167-021-06676-8>.
- Pornrattanamaneeewong C, Narkbunnam R, Chareancholvanich K. Medial proximal tibial angle after medial opening wedge HTO: a retrospective diagnostic test study. *Indian J Orthop*. Sep 2012;46(5):525–530. <https://doi.org/10.4103/0019-5413.101042>.
- Giffin JR, Vogrin TM, Zantop T, Woo SL, Harner CD. Effects of increasing tibial slope on the biomechanics of the knee. *Am J Sports Med*. Mar 2004;32(2):376–382. <https://doi.org/10.1177/0363546503258880>.
- Imhoff FB, Mehl J, Comer BJ, et al. Slope-reducing tibial osteotomy decreases ACL-graft forces and anterior tibial translation under axial load. *Knee Surg Sports Traumatol Arthrosc*. Oct 2019;27(10):3381–3389. <https://doi.org/10.1007/s00167-019-05360-2>.
- Jones GG, Jaere M, Clarke S, Cobb J. 3D printing and high tibial osteotomy. *EFORT Open Rev*. May 2018;3(5):254–259. <https://doi.org/10.1302/2058-5241.3.170075>.
- Kim KK, Song J. Accuracy of patient-specific instrument for cylindrical axis implementation in kinematically aligned total knee arthroplasty. *Clin Orthop Surg*. Oct 2023;15(5):760–769. <https://doi.org/10.4055/cios22147>.
- Dasari SP, Hevesi M, Mameri E, et al. Patient-specific instrumentation for medial opening wedge high tibial osteotomies in the management of medial compartment osteoarthritis yields high accuracy and low complication rates: a systematic review. *J isakos*. Jun 2023;8(3):163–176. <https://doi.org/10.1016/j.isako.2023.02.001>.
- Pang R, Jiang Z, Xu C, et al. Is patient-specific instrumentation accurate and necessary for open-wedge high tibial osteotomy? A meta-analysis. *Orthop Surg*. Feb 2023;15(2):413–422. <https://doi.org/10.1111/os.13483>.
- Fürnstahl P, Vlachopoulos L, Schweizer A, Fucentese SF, Koch PP. Complex osteotomies of tibial Plateau malunions using computer-assisted planning and patient-specific surgical guides. *J Orthop Trauma*. Aug 2015;29(8):e270–e276. <https://doi.org/10.1097/bot.0000000000000301>.
- Yoo JH, Chang CB, Shin KS, Seong SC, Kim TK. Anatomical references to assess the posterior tibial slope in total knee arthroplasty: a comparison of 5 anatomical axes. *J Arthroplast*. Jun 2008;23(4):586–592. <https://doi.org/10.1016/j.arth.2007.05.006>.
- Yoon JR, Koh YY, Lee SH. Estimation of the proper gap ratio using preoperative radiography for posterior tibial slope maintenance in biplanar open wedge high tibial osteotomy. *J Orthop Surg Res*. Mar 20 2023;18(1):219. <https://doi.org/10.1186/s13018-023-03712-w>.
- Ozalay M, Ozkoc G, Circi E, et al. The correlation of correction magnitude and tibial slope changes following open wedge high tibial osteotomy. *Knee Surg Sports Traumatol Arthrosc*. Oct 2008;16(10):948–951. <https://doi.org/10.1007/s00167-008-0589-8>.
- Ozel O, Yucel B, Mutlu S, Orman O, Mutlu H. Changes in posterior tibial slope angle in patients undergoing open-wedge high tibial osteotomy for varus gonarthrosis. *Knee Surg Sports Traumatol Arthrosc*. Jan 2017;25(1):314–318. <https://doi.org/10.1007/s00167-015-3571-2>.
- Rubino LJ, Schoderbek RJ, Golish SR, Baumfeld J, Miller MD. The effect of plate position and size on tibial slope in high tibial osteotomy: a cadaveric study. *J Knee Surg*. Jan 2008;21(1):75–79. <https://doi.org/10.1055/s-0030-1247798>.
- Jacquet C, Sharma A, Fabre M, et al. Patient-specific high-tibial osteotomy's 'cutting-guides' decrease operating time and the number of fluoroscopic images taken after a brief learning curve. *Knee Surg Sports Traumatol Arthrosc*. Sep 2020;28(9):2854–2862. <https://doi.org/10.1007/s00167-019-05637-6>.
- Fucentese SF, Meier P, Jud L, et al. Accuracy of 3D-planned patient specific instrumentation in high tibial open wedge valgisation osteotomy. *J Exp Orthop*. Feb 27 2020;7(1):7. <https://doi.org/10.1186/s40634-020-00224-y>.

24. Chaouche S, Jacquet C, Fabre-Aubrespy M, et al. Patient-specific cutting guides for open-wedge high tibial osteotomy: safety and accuracy analysis of a hundred patients continuous cohort. *Int Orthop*. Dec 2019;43(12):2757–2765. <https://doi.org/10.1007/s00264-019-04372-4>.
25. Tardy N, Steltzlen C, Bouguennec N, et al. Is patient-specific instrumentation more precise than conventional techniques and navigation in achieving planned correction in high tibial osteotomy? *Orthop Traumatol Surg Res*. Dec 2020;106(8s): S231–s236. <https://doi.org/10.1016/j.otsr.2020.08.009>.
26. Mao Y, Xiong Y, Li Q, et al. 3D-Printed patient-specific instrumentation technique Vs. Conventional technique in medial open wedge high tibial osteotomy: a prospective comparative study. *BioMed Res Int*. 2020;2020, 1923172. <https://doi.org/10.1155/2020/1923172>.