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Hinge fracture in lateral closed-wedge distal femoral osteotomy in knees undergoing double-level osteotomy: assessment of postoperative change in rotational alignment using CT evaluation

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Abstract

Purpose The purpose of this study was to examine the radiological features of hinge fracture occurring at the distal medial femoral cortex in knees undergoing biplanar lateral closed-wedge distal femoral osteotomy (LCW-DFO) in double-level osteotomy (DLO) based on pre- and postoperative CT image analyses. It was hypothesised that medial hinge fractures in LCW-DFO would occur with a similar incidence to that in high tibial osteotomy, and its occurrence would affect the clinical/radiological outcomes and induce unintended change in alignment depending on the fracture type (direction of the fracture).

Methods A consecutive series of 36 knees (31 patients) with primary varus osteoarthritis undergoing DLO comprised the study population. The mean age at surgery was 62.0 ± 5.9 years. Presence of hinge fracture was assessed on radiographs and CT images at 1 week. The fracture type was classified depending on the direction of the fracture line: crack propagation in line with the osteotomy (type 1) and fractures extending proximally (type 2) or distally (type 3) from the tip of the wedge. Computer-assisted assessments of bony limb alignment and bony geometry were conducted on a full-length weight-bearing radiograph and CT images using image analysis software. In addition, subjective clinical results were evaluated using the Knee Injury and Osteoarthritis Outcome Score (KOOS). Radiological and clinical follow-up results at 1 and 2 years were compared to the preoperative data, while comparative analysis was made between the subjects with and without a hinge fracture.

Results Postoperative image examinations revealed type 1 and 2 medial femoral hinge fractures in 4 and 7 knees, while no type 3 fracture was identified in the study population. Consequently, the overall incidence of the hinge fracture was 30.6% (11 of the 36 knees). Four of those 11 fractures (36.4%) could not be detected on plain radiographs. CT image analysis for three-dimensional bony geometry showed greater increase in internal rotation of the distal bony segment (increased femoral antetorsion by 9.5° on average) after surgery compared to the knees without a hinge fracture ($P = 0.01$). Clinical evaluation using the KOOS at 2 years showed no significant difference between the groups with and without hinge fractures.

Conclusion In LCW-DFO, medial femoral hinge fractures occurred in 30.6% of the cases. Knees with type 1 hinge fracture exhibited significantly greater increase in femoral antetorsion as compared to those without hinge fracture. In this case series, postoperative weight-bearing protocol was delayed for knees with hinge fracture. Consequently, surgical results were not affected by the occurrence of hinge fracture for up to 2 years.

Level of evidence IV (case series)

Keywords Double-level osteotomy · Distal femur osteotomy · Hinge fracture · Osteoarthritis · Osteotomy · Hinge

Introduction

Osteotomy around the knee is a well-established and commonly adopted surgical option for knees with uni-compartmental osteoarthritis [4, 26, 39, 42, 45]. There are several surgical options for the mode and the level of osteotomies. Among those, correction by a single-level isolated high tibial

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osteotomy (HTO) in knees with severe varus deformity has been shown to result in non-anatomical joint line obliquity which induces subsequent problems such as increased shear force at the cartilage [1, 3, 13, 31, 34, 35, 38, 42, 46, 48]. Double-level osteotomy (DLO) combining a lateral closed-wedge distal femoral osteotomy (LCW-DFO) [5, 9] and a medial open-wedge high tibial osteotomy (MOW-HTO) [15, 26, 45] was introduced with the intent to anatomically reconstruct the bony geometry and limb alignment [1–3, 31, 38]. In recent years, development of minimally invasive osteotomy techniques with improved surgical instruments has reduced the rate of operative complications and expanded its indication [27, 39, 50]; however, there are still some complications associated with the procedure. Hinge fracture is among those problems which may impair the surgical outcomes.

Hinge fractures in open-wedge osteotomy were documented by Takeuchi et al. [47] for fractures around the lateral tibial cortex in MOW-HTO. They classified this fracture depending on the direction of the fracture and showed that the fracture extending distally to the osteotomy induced subsequent complications such as delayed union and correction loss. Subsequent to this report, there have been a number of papers dealing with lateral hinge fractures after MOW-HTO [12, 20, 22–24, 44]. However, there is a paucity of relevant information for CW-DFO [8, 21, 32]. Moreover, previous relevant studies reporting clinical consequences of the hinge fracture were focused on bony healing and coronal plane alignment in plain radiographic examination, though rotational malalignment of the lower limb on the axial plane has been also shown to substantially influence the biomechanical environment in the knee [5, 9, 18, 25].

In this study, pre- and postoperative CT examinations were included in the analytical measures, which enabled accurate assessments of fracture line and three-dimensional alignment. The purpose of this study was to examine the radiological features of hinge fractures occurring at the distal medial femoral cortex in knees undergoing LCW-DFO in DLO based on CT image analyses. It was hypothesised that medial hinge fracture would be identified after MOW-DFO with a similar incidence to that in HTO, and its occurrence would affect the clinical/radiological outcomes and induce unintended change in alignment depending on the fracture type (direction of the fracture).

Patients and methods

Study population

A consecutive series of knees with severe varus osteoarthritis (more than 10° of varus) that met our surgical indication and underwent DLO during the study period from January 2014 to August 2017 were initially included in the study. The patients were followed up for a minimum of 2 years. During the process of data acquisition, subjects without complete radiological/clinical data set were excluded from the study population. The design of this study was approved by the Review Board of Hyogo College of Medicine (No. 2218).

Surgical indication and planning

Among various osteotomy options, DLO was adopted when there were combined varus deformities both in the distal femur and the proximal tibia. At preoperative surgical planning using digital planning software (mediCAD, Hectec, Germany), first, the mechanical lateral distal femoral angle (mLDFA, normal value; 85°–90°), the mechanical medial proximal tibial angle (mMPTA, normal value; 85°–90°) and the joint line convergence angle (JLCA, normal value; 0°–2°) [33] were measured. Then, surgical simulation was initiated with isolated MOW-HTO. During the simulation and planning of the osteotomy, the intended mechanical tibiofemoral angle (mTFA) was set to 1° (a slightly valgus position) corresponding to %weight-bearing line of 52% [31]. If the predicted mMPTA in the surgical simulation was 95° or greater (or the wedge size was 15 mm or greater), then DLO was considered as an option and surgical planning for DLO was conducted accordingly [30, 31].

Surgical procedure

All surgeries were performed by the first author (H.N.). Detailed descriptions of our surgical procedures have been made in our previous paper [30]. DLO was performed using a minimally invasive biplanar osteotomy technique combined with a locking compression plate (LCP) fixation. The osteotomy procedure was conducted under fluoroscopic control following the technique developed by a working group from the Netherlands organized by van Heerwaarden [11]. The femoral osteotomy was conducted first using the minimally invasive plate osteosynthesis (MIPO) technique [27, 50]. The TomoFix medial distal femur (MDF) anatomical plate (DePuy Synthes, Solothurn, Switzerland) originally designed for the contralateral femur was bent according to the individual's anatomy and used for fixation. Subsequently, the surgery was completed with MOW-HTO via a technique which was previously described by Lobenhoffer and Staubli [26, 30, 42, 45].

Postoperative rehabilitation

The operated knee was not immobilised after surgery. Range of motion exercise was initiated on the following day as tolerated. Partial weight-bearing with one third of body weight using crutches was allowed at 3 weeks with progression to full weight-bearing at 4 weeks. If a hinge fracture was identified in postoperative imaging examination, full weight-bearing was delayed and not permitted until after callus formation of the hinge fracture site was identified [29].

Postoperative follow-up

Postoperative follow-up evaluations were periodically performed every 3 months within a year and then every 6 months afterwards. Comprehensive radiological and clinical evaluations were conducted at 1 year and 2 years, and the results were compared to the preoperative status. The first author (H.N.) performed the periodical clinical and radiological follow-up examinations.

Data acquisition

A non-weight-bearing radiograph was taken at 1 week after surgery, and the presence of hinge fractures in the distal femur was assessed on anteroposterior radiograph. In addition, CT examination was performed on all knees preoperatively and at 1 week post-operation with the informed consent of each patient and the patient's family. CT images were acquired using a 256-slice multidetector CT scanner (SOMATOM Definition Edge, Siemens Healthineers, Erlangen, Germany), and sequential images from the hip joint to the ankle joint were obtained with a 0.7-mm slice thickness, 40-cm field of view, and 512 × 512 matrix (pixel size: 0.78 mm).

Classification of the hinge fractures

Evaluation of hinge fractures was made on coronal CT images around the femoral osteotomy site. If the fracture line extending from the end of the osteotomy breached the medial femoral cortex, the diagnosis of a medial femoral hinge fracture was made. Based on the orientation of the fracture line, the following classification was made: type 1, a fracture extending to the medial cortex in line with the osteotomy; type 2, a fracture breaching the medial cortex proximally to the osteotomy line (Fig. 1); and type 3, a fracture extending distally from the osteotomy.

Evaluation of the alignment and bony geometry

Radiological parameters of the limb alignment and bony geometry were measured on a long-leg weight-bearing radiograph using an image analysis software (mediCAD®, Hectec, Germany) [43]. Radiographic examinations for measurement of those parameters were conducted preoperatively and at 1 and 2 years after surgery.

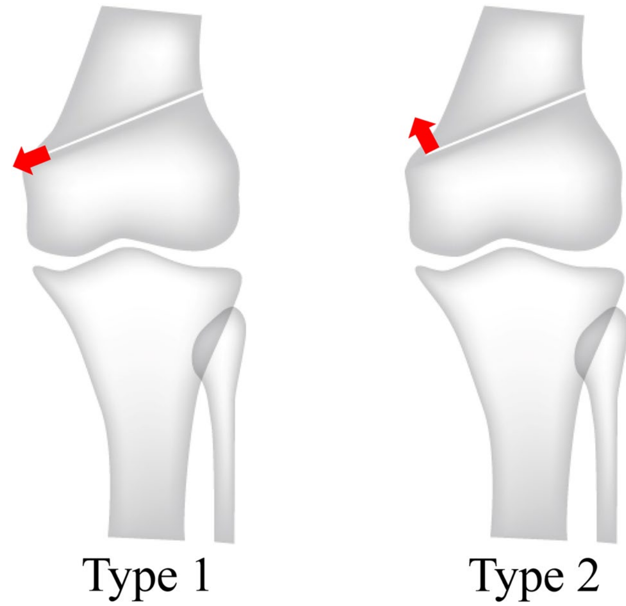

Fig. 1 Classification of medial hinge fractures in LCW-DFO. Type 1: the fracture extends to the medial cortex in line with the osteotomy. Type 2: the fracture breaches the medial cortex proximal to the osteotomy

Measurement of femoral torsion

After extracting the Digital Imaging and Communications in Medicine (DICOM) data from the Picture Archiving and Communication System (PACS) software, the CT image data were imported into ZioCube imaging software (Ziosoft Inc, Japan) for measurement of femoral torsion. The femoral torsion was measured following the Waidelich method [40, 51]. First, the axial images of the femoral head and the trochanter, as well as the femoral condyle, were selected. The proximal joint line was defined through centres of circle/ellipses of the femoral head and the greater trochanter; while, the distal reference line was defined as the tangent line to the posterior edges of the lateral/medial femoral condyles. The angle between the proximal and distal reference lines was used to measure femoral torsion.

To match the three-dimensional orientation of the preoperative image with that of the postoperative image, a longitudinal axis of the femur was established in three-dimensional CT images and used as a reference axis (Fig. 2). In addition, the level of the slice showing the same bony contour and geometry was selected for the comparative analysis at the two time periods.

Reliability of the CT measurement was assessed via intraclass correlation coefficients (ICC). In assessment of the intra- and interrater reliabilities, the images of 10 randomly selected subjects were subjected to the analysis. Repeated measurements by a rater with one-week time interval as well as independent measurements by 2 raters

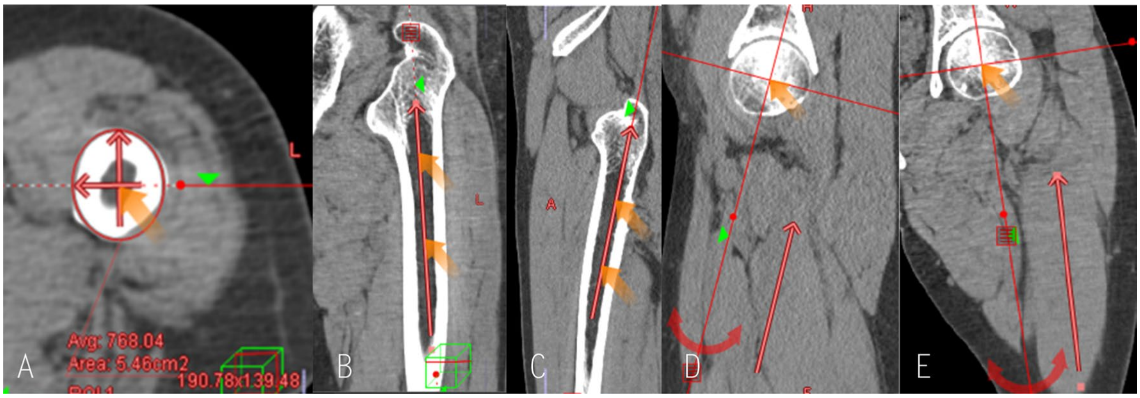

Fig. 2 Matching of pre- and postoperative CT images. **a** The axial centre of the femoral shaft is identified on the axial images at two levels of the proximal femur. **b**, **c** The longitudinal axis of the femur is established by connecting the two axial centre points on coronal and sagittal planes. **d**, **e** In order to match the three-dimensional orientation of the preoperative image with that of the postoperative image, one of the images at the two time periods is rotated around the centre of the femoral head on coronal and sagittal planes until matching of the longitudinal axis is achieved

(S.K. and R.U.) were conducted. Consequently, high ICC values of more than 0.9 were demonstrated for both analyses. Based on the high repeatability confirmed by the reliability analysis, measurement results derived from a single rater's assessment (S.K.) were adopted in the study.

Clinical outcome evaluation

Clinical outcome was evaluated using the validated patient-reported outcome measure, Knee Injury and Osteoarthritis Outcome Score (KOOS) [7, 37]. The evaluations were conducted at 1 and 2 years after surgery and the per- and postoperative results were statistically compared.

Statistical analysis

Changes from the preoperative to postoperative parameter values in each group were statistically assessed using the Mann–Whitney's *U* test, while comparison among the three groups was analysed using one-way ANOVA with post hoc Turkey's test. Statistically significant level was set at $P < 0.05$.

A power analysis was conducted using STATA for comparison of the femoral torsion values between the groups. The analysis was conducted using the mean and SD values derived from this study. Femoral torsion angle was adopted as the primary outcome measure. The sample size in the comparative group was assumed to be equal. Consequently, it was shown that 12 subjects in each group would be necessary to detect the significant difference using the two-sided test at a power of 90% and $P < 0.05$.

Results

Study population

A consecutive series of 55 knees in 42 patients who underwent DLO in our institute between January 2014 and August 2017 were initially enrolled in the study. Among those, 19 knees in 11 patients were subsequently excluded from the analysis due to the lack of complete image data set, leaving 36 knees in 31 patients as subjects for the data analyses of the present study. The study population comprised of 6 males and 25 females, and the mean age of the included patients was 62.0 ± 5.9 years (range 54–75 years). Clinical follow-up data of more than 2 years after surgery were available for all 31 patients with the mean follow-up period of 37.0 ± 5.0 months (range 30–46 months).

Occurrence of hinge fractures

In the 36 included knees, type 1 and 2 medial hinge fractures were identified in 4 and 7 knees, respectively; while no type 3 fracture was encountered in this case series. Consequently, the overall incidence among the study population was 30.6% (11 of the 36 knees). Hinge fractures could not be detected on plain radiograph in 1 of the 4 type 1 and 3 of the 7 type 2 fractures. Therefore, in total, plain radiograph failed to reveal 4 of the 11 hinge fractures with a diagnostic failure rate of 36.4% (Fig. 3).

Radiological results

Bony union was uneventfully attained in all knees, though the postoperative time period for full weight-bearing was

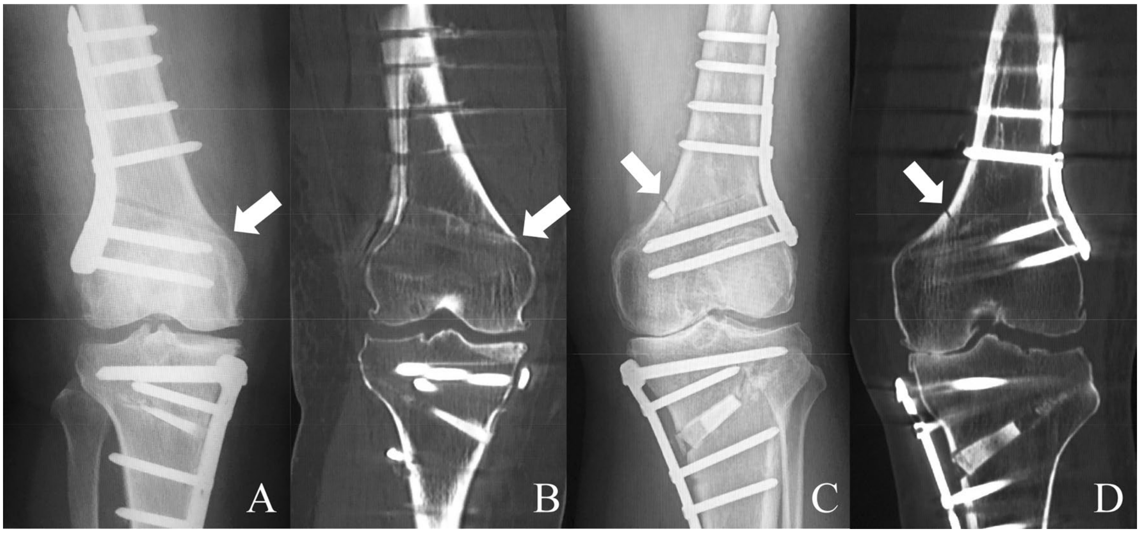

Fig. 3 Representative radiological and CT image findings for type 1 and type 2 hinge fracture (arrow). Type 1 fracture. **a** Anteroposterior radiograph. **b** Coronal CT image. Type 2 fracture. **c** Anteroposterior radiograph. **d** Coronal CT image

delayed in patients with hinge fractures. As shown in Table 1, radiological measurements at 1- and 2-year follow-up evaluations showed restoration of normal knee alignment and bony geometry with the mean mTFA and mLDFA corrected to normal ranges. Restoration of normal limb alignment and bony geometries was achieved in both of the groups with and without hinge fractures, and the occurrence of hinge fractures did not affect the radiological outcomes in either type 1 or type 2 hinge fracture groups.

In the CT examinations for rotational on the axial plane, the mean preoperative torsion of the femur in the total study population was 28.7° ± 9.5° (range 7.6°–56.9°). After the osteotomy, the bony segment distal to the osteotomy exhibited a small increase in internal torsion with the mean increase of 1.6° ± 2.8° (range 4.1° external rotation–6.2° internal rotation) in knees without hinge fractures. In knees with a type 1 hinge fracture, the distal segment was internally rotated (femoral torsion was increased) by 9.5° ± 8.0° on average (range 2.8°–20.8° internal rotation), which was significantly larger than that in knees without hinge fractures ($P = 0.01$). In knees with a type 2 hinge fracture, internal rotation of the distal segment increased by 3.1° ± 5.4° on average (range 3.4° external rotation–6.2° internal rotation) without significant difference in postoperative rotational change compared to the knees with no hinge fracture ($P = 0.51$) (Table 2).

Clinical results

During the study period, no intra- and early postoperative complications requiring additional management were encountered, except for hinge fractures. A hinge fracture in one case was managed with additional fixation using a medial support plate for augmentation of fixation stability.

Clinical outcomes using the KOOS significantly improved after surgery in both groups with and without hinge fractures. The occurrence of hinge fractures did not affect the clinical outcomes in either type 1 or type 2 hinge fracture groups (Table 3).

Table 1 Pre- and postoperative radiological parameter values of alignment and bony geometry

	Preoperative measurement		Postoperative measurement at 1 year		Postoperative measurement at 2 years	
	mLDFA (°)	mTFA (°)	mLDFA (°)	mTFA(°)	mLDFA (°)	mTFA (°)
No hinge fracture group (*n*: 25)	90.5 ± 1.9	− 14.0 ± 2.6	86.0 ± 1.6	− 1.4 ± 2.2	86.0 ± 1.7	− 1.0 ± 2.6
Type 1 hinge fracture group (*n*: 4)	90.2 ± 0.7	− 14.2 ± 3.6	86.6 ± 1.0	− 2.2 ± 2.3	86.6 ± 0.6	− 2.0 ± 2.2
Type 2 hinge fracture group (*n*: 7)	90.5 ± 2.6	− 14.4 ± 2.4	85.4 ± 1.7	− 1.8 ± 1.7	85.7 ± 1.6	− 1.8 ± 0.4

No significant differences were found between the groups by one-way ANOVA with post hoc Tukey's test

mLDFA mechanical lateral distal femoral angle (normal range 85°–90°), *mTFA* mechanical tibiofemoral angle

Table 2 Mean internal rotation of the distal bony segment (femoral antetorsion)

	No hinge fracture group (n: 25)		Type 1 hinge fracture group (n: 4)	Type 2 hinge fracture group (n: 7)
Preoperative antetorsion	30.8 ± 9.6°		27.1 ± 6.8°	22.5 ± 8.7°
Postoperative antetorsion	32.3 ± 10.5°		36.6 ± 8.5°	25.7 ± 10.3°
Increase internal rotation angle	1.6 ± 2.8°	—— * ——	9.5 ± 8.0°	3.1 ± 5.4°

*Internal rotation of the distal segment significantly increased in knees with type 1 hinge fracture compared to knees without a hinge fracture *(P* = 0.01).

Table 3 Pre- and postoperative clinical results assessed by the Knee Injury and Osteoarthritis Outcome Score (KOOS)

n: 36	Preoperative	Postoperative (at 1 year)	Postoperative (at 2 years)
No hinge fracture group (*n*: 25)	210.6 ± 78.4	361.4 ± 45.9	393.1 ± 53.7
Type 1 hinge fracture group (*n*: 4)	227.5 ± 50.6	353.0 ± 50.3	394.5 ± 83.3
Type 2 hinge fracture group (*n*: 7)	180.2 ± 63.4	326.8 ± 78.6	386.3 ± 28.8

No significant differences were found between the groups by one-way ANOVA with post hoc Tukey's test

Discussion

The most important finding in the present study is that the medial femoral hinge fracture occurred in 30.6% of the knees undergoing LCW-DFO. Furthermore, we described two types of hinge fractures based on the location of breaching within the medial femoral cortex. The fracture line extended in line with the osteotomy in type 1 fractures, while type 2 fractures breached the femoral cortex proximally to the osteotomy. When the hinge fracture was identified, postoperative weight-bearing protocol was delayed in this case series. Consequently, no significant differences in clinical and radiological outcomes were noted between the knees with and without hinge fractures. In knees with type 1 fracture, however, significant rotational change at the osteotomy site was noted on postoperative CT evaluation.

A lateral tibial hinge fracture as a complication of MOW-HTO has been reported in a number of studies [12, 20, 22–24, 26, 44, 47]. The overall incidence of hinge fractures following LCW-DFO in this case series (30.6%) was similar to that reported in those previous studies. Takeuchi et al. classified the hinge fracture in MOW-HTO depending on the direction of the fracture line (proximal, in line with the osteotomy, and distal) [47]. In the present series, the hinge fracture extending distally toward the articular surface which corresponds to Takeuchi type III fracture was not encountered. Presence of compliant cancellous bone with a substantial thickness in the femoral condyle may have served as an intervening barrier to prevent the distal extension of the fracture to in LCW-DFO.

As clinical consequences of the hinge fracture, subsequent problems such as over- or under-correction [29, 47] and delayed bone healing [29, 41] were reported in MOW-HTO. In the present study for LCW-DFO, however, the occurrence of hinge fractures did not affect the postoperative outcomes. In this case series, weight-bearing in the postoperative rehabilitation programme was delayed for knees with the hinge fracture and this management modification may have been a factor which effectively avoided the unfavourable sequence.

Although the clinical outcomes were not affected by the hinge fracture, CT evaluation showed increased internal rotation of the distal femoral bony segment (increased femoral antetorsion), especially in knees with type 1 fracture. The fracture plane in the type 1 fracture is extension of the osteotomy plane and flat, and thus, resistance to rotational motion is thought to be small. Previous cadaveric studies have shown that increased femoral antetorsion induced valgus deviation of the mechanical axis [5, 18]. In addition, biomechanical studies have shown that internal rotation of the distal femur results in increased patellofemoral contact stress [9, 25]. In total knee arthroplasty, internal rotation of the femoral component causes several unfavourable sequelae such as patellar maltracking and non-physiologic flexion kinematics [14, 17, 28, 36, 49]. Therefore, rotation at the osteotomy site as observed in this study may alter the mechanical

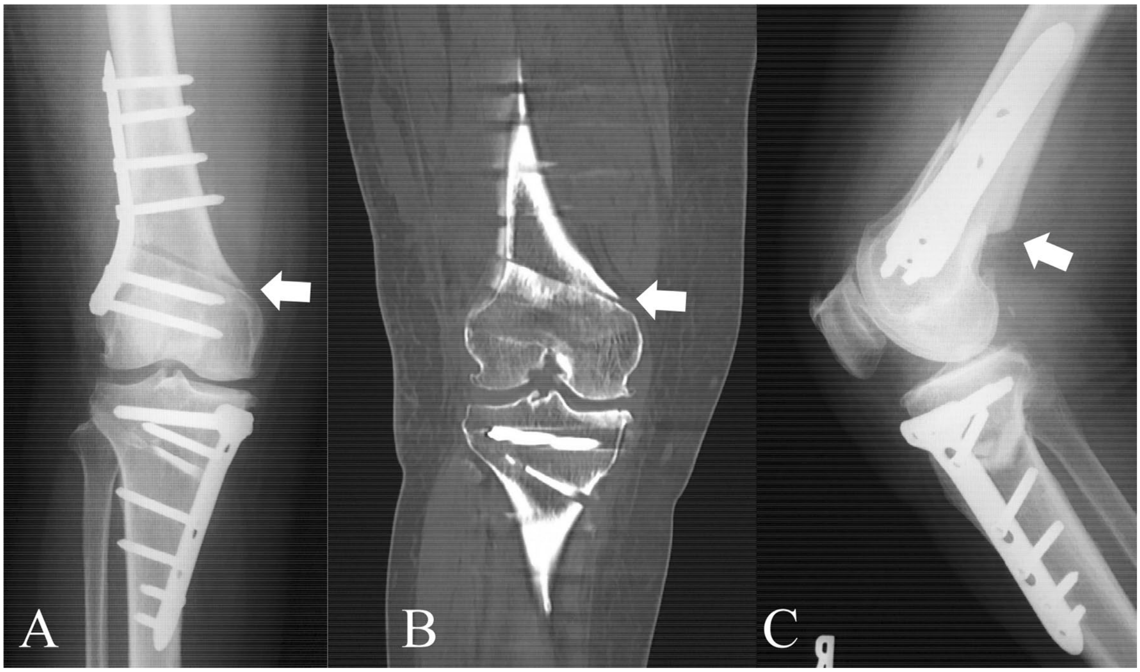

Fig. 4 Postoperative image findings of the knee with type 1 fracture exhibiting increased femoral torsion. **a** Anteroposterior radiograph (arrow). **b** Coronal CT image (arrow). **c** The distal femur is displaced due to the increased internal torsion (arrow)

environment in the knee, potentially affecting the surgical outcomes. Further follow-up study is required to clarify long-term consequence of the rotational malalignment.

As regards prevention of the hinge fracture, its aetiology should be considered. Regarding the surgical factor, bony cut beyond the hinge point may lead to type 1 fracture; while, inadequate cut (mostly at the posterior cortex) with forceful wedge closing may cause type 2 fracture. To prevent the occurrence of hinge fractures, surgeons should carefully check the extent of osteotomy through inspection and fluoroscopic control during surgery. Previous papers dealing with hinge fractures in medial CW-DFO, other factors such as clearance of the gap following wedge resection, careful and slow wedge closure, and selection of appropriate hinge position (upper border of the femoral condyle rather than supracondylar region) have been listed as surgical knacks for the fracture prevention [21, 32]. Csernátony et al. [8] have proposed a new preventive measure by making an additional juxtacortical drill hole at the end of the osteotomy to reduce the local stress during wedge opening/closing.

As for the rotational change observed for knees with type 1 hinge fracture, it has been reported that osteosynthesis of distal femoral fractures using the MIPO technique is linked to rotational malalignment at a substantially high rate [6, 19]. When occurrence of the hinge fracture is noted during surgery, surgeons should cope with the risk for impaired stability (Fig. 4). Supplemental plate fixation on the medial side as well as close inspection of the fitting between the osteotomy surfaces through wider exposure can be countermeasures to cope with those potential problems. When the hinge fracture was recognised postoperatively, timing of weight-bearing should be delayed to avoid subsequent complications such as delayed bony healing.

There were several limitations included in this study. First, the study population was small, and thus, the study was underpowered. Therefore, type II error in the statistical analysis was likely to occur. Second, there are potential sources of errors included in the comparative CT image analysis for femoral torsion assessment. Although attempts were made to select the pre- and postoperative axial CT images with the same orientation and level, perfect image matching is theoretically not feasible leading to an assessment error. Moreover, the images analysis was conducted by a single observer, though a high ICC value (> 0.9) was confirmed. Third, complete osteotomy cut during surgery may not have been differentiated from type 1 hinge fracture in this series. Fourth, the differences in postoperative rotational change between the groups with and without a hinge fracture was small; thus, its clinical significance is unclear. Further follow-up study for a longer period is warranted. Fifth, we evaluated the hinge fracture by CT and radiograph taken at 1 week after surgery. Therefore, hinge fractures occurring after this time period could not be detected. Finally, there are still some potential factors related to the occurrence of hinge fractures such as bone quality (density) and osteotomy length/inclination that are not analysed in this study.

Identification of the risk factors in multiple aspects would help to prevent this complication.

Conclusion

In LCW-DFO, medial femoral hinge fractures occurred in 30.6% of the cases. Knees with type 1 hinge fracture exhibited significantly greater increase in femoral antetorsion as compared to those without hinge fracture. In this case series, postoperative weight-bearing protocol was delayed for knees with hinge fracture. Consequently, surgical results were not affected by the occurrence of hinge fracture for up to 2 years.

Compliance with ethical standards

Conflict of interest All authors have nothing to disclose that could have direct or potential influence or impart bias on the work.

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Ethical approval The study was approved by Ethics Committee and judged at Hyogo College of Medicine (reference no. 2218).

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