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First metacarpal extension-abduction osteotomy effect on joint remodeling and articular cartilage repair in thumb carpometacarpal osteoarthritis

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Abstract

Background The first metacarpal osteotomy is a joint-preserving surgery for thumb carpometacarpal (CMC) osteoarthritis that improves pain and function. However, its effects on joint remodeling and articular cartilage repair under physiological conditions remain unclear. This study aimed to clarify these aspects using computed tomography (CT)-based subchondral bone density analysis and arthroscopic evaluation.

Methods Fifteen hands of 14 patients who underwent a first metacarpal extension-abduction osteotomy for thumb CMC osteoarthritis were included. CT scans were performed preoperatively and one year postoperatively to assess changes in subchondral bone density (measured in Hounsfield units [HU]) across nine regions of the first metacarpal and trapezium articular surfaces. Arthroscopic evaluation of the articular cartilage was performed at the time of osteotomy and at implant removal one year postoperatively using the International Cartilage Repair Society (ICRS) grading scale.

Results Preoperatively, higher HU values (median [interquartile range]) were observed in the palmar regions of the first metacarpal (758 [643–803] HU) and the central regions of the trapezium (898 [867–960] HU). One year after osteotomy, these values decreased significantly in these initially high-stress regions (first metacarpal palmar regions: 433 [307–475] HU, $p<.001$; trapezium central regions: 571 [508–649] HU, $p<.001$; Wilcoxon matched-pairs signed rank test), indicating a more uniform stress distribution. Arthroscopic evaluation revealed improvements in ICRS grade in five out of nine cases on the metacarpal side and four out of nine cases on the trapezium side.

Conclusions The first metacarpal extension-abduction osteotomy alters the abnormal stress distribution patterns in thumb CMC osteoarthritis, leading to a more uniform stress distribution across the joint. Arthroscopic findings suggest that articular cartilage repair may occur following osteotomy. These results provide new insights into the mechanisms underlying the clinical benefits of this procedure and support its use as a joint-preserving surgery for thumb CMC osteoarthritis.

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Keywords Thumb carpometacarpal osteoarthritis, First metacarpal osteotomy, Joint remodeling, Stress distribution, Articular cartilage repair

Background

Thumb carpometacarpal (CMC) osteoarthritis leads to pain and limited range of motion due to arthritic changes and joint subluxation [1, 2]. The first metacarpal osteotomy, introduced by Wilson in 1973, is mainly performed for younger patients or those with early-stage osteoarthritis [3–5]. This joint-preserving surgery allows for future surgical options, such as arthroplasty or arthrodesis. Reports indicate improvement in pain, pinch strength, and patient-reported outcomes, with good long-term clinical results [6–12].

Biomechanical effects of the first metacarpal osteotomy have been demonstrated in cadaver studies, showing a palmar shift of the load center and increased joint stability due to improved joint subluxation and ligament laxity [13–15]. However, these studies do not clarify changes in the joint under physiological conditions post-osteotomy. Localized loading in the joint induces subchondral mineralization, which can be quantitatively evaluated using Hounsfield unit (HU) values from computed tomography (CT) images [16, 17]. HU values, calculated from the linear attenuation coefficients of CT images, reflect the radiodensity of tissues [18, 19]. This method enables the assessment of stress distribution patterns in patients with thumb CMC osteoarthritis and the changes in stress distribution under actual physiological loading conditions after osteotomy [20, 21].

Joint remodeling with changes in stress distribution and cartilage repair after osteotomy has been reported in knee and ankle osteoarthritis [22–24]. However, in the first metacarpal osteotomy, a joint-preserving surgery for similar osteoarthritis, changes in articular cartilage after surgery have not yet been clarified. This study aimed to clarify the effects of first metacarpal extension-abduction osteotomy on stress distribution and cartilage repair in the thumb CMC joint. We hypothesized that joint remodeling with changes in stress distribution and articular cartilage repair would occur as a result of osteotomy.

Methods

Study design and patient selection

We conducted a CT-based study on the postoperative range of motion in thumb CMC osteoarthritis, which was approved by the Ethics Committee of Hiroshima University (approval number: E-2344). This ongoing study, which has not yet yielded published results, included patients who underwent surgery (arthrodesis, arthroplasty, or first metacarpal osteotomy) for thumb CMC joint pain between March 2018 and May 2023, with CT scans performed preoperatively and 1 year postoperatively. Patients with systemic inflammatory diseases such as rheumatoid arthritis or gout, neurological disorders, and traumatic thumb CMC osteoarthritis were excluded. Healthy volunteers without radiographic signs of osteoarthritis were recruited as controls and underwent CT scans. The operating surgeon (A.K.) determined the surgical method based on the Eaton stage and the patient's lifestyle and preferences.

This study was a retrospective analysis using a subset of data from the ongoing CT-based study, focusing on patients who underwent a first metacarpal osteotomy. Additional informed consent was obtained from all the patients and volunteers. At 1 year postoperatively, no patients had complaints related to the plate, and implant removal was performed upon request.

Surgical technique

First, the articular cartilage of the CMC joint was evaluated using a 1.9 mm arthroscope through the 1-R portal (radial side of the abductor pollicis longus tendon) and the 1-U portal (ulnar side of the extensor pollicis brevis tendon). Synovectomy was performed simultaneously. The first metacarpal osteotomy was performed on the dorsal aspect, approximately 1 cm distal to the CMC joint surface. An initial osteotomy cut was made parallel to the CMC joint surface using a microsurgical saw, carefully preserving the palmar hinge as much as possible. Next, to achieve approximately 30° extension and 10° abduction, a closing wedge osteotomy was performed under fluoroscopic guidance, confirming the joint surface angle. A wedge measuring approximately 7 mm radially and 5 mm ulnarly was removed from the initial osteotomy line. The osteotomy site was then closed and compressed, and fixation was achieved using a variable angle locking hand system 1.5 mm plate (DePuy Synthes, Raynham, MA, USA) (Fig. 1).

Postoperative osteotomy angle assessment

To assess the accuracy of the surgical correction, preoperative and postoperative plain radiographs were analyzed [25]. The achieved extension angle was calculated from the change between preoperative and postoperative measurements on the lateral view (volar tilt), which is the angle between a line drawn along the dorsal cortex of the first metacarpal shaft distal to the osteotomy and a line connecting the two most proximal points of the proximal articular surface. The achieved abduction angle was calculated from the change between preoperative and postoperative measurements on the posteroanterior view (first metacarpal shaft angle), which is the angle between

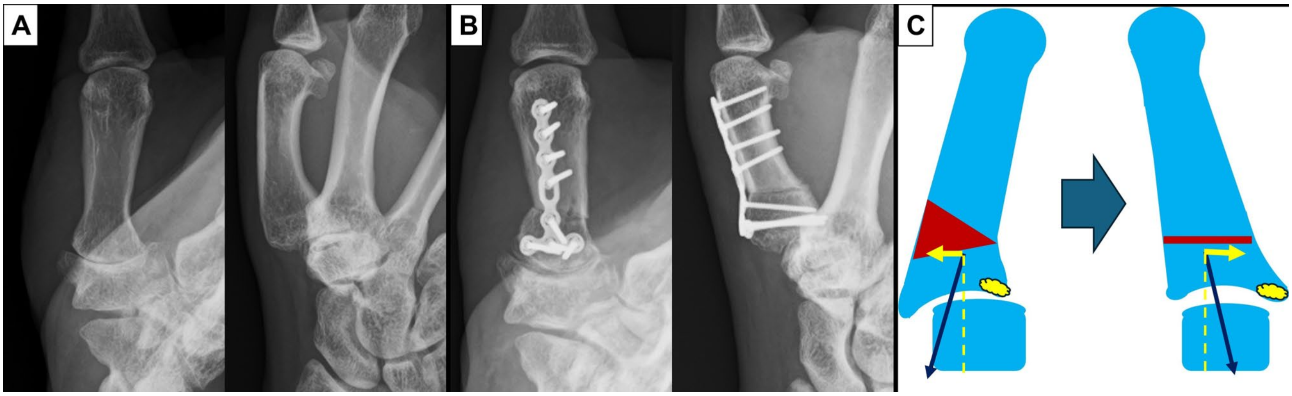

Fig. 1 (**A**) Preoperative radiograph of a 47-year-old man with Eaton stage III thumb carpometacarpal osteoarthritis. (**B**) Postoperative radiograph following first metacarpal extension-abduction osteotomy, demonstrating improvement in dorsal subluxation. (**C**) Illustrative diagram demonstrating biomechanical changes after osteotomy. Preoperatively, the combined effect of joint force (yellow dotted line) and axial loading (black arrow) produces dorsal subluxation of the metacarpal (yellow arrow). After osteotomy, the redirected axial force generates a palmar-directed force on the metacarpal

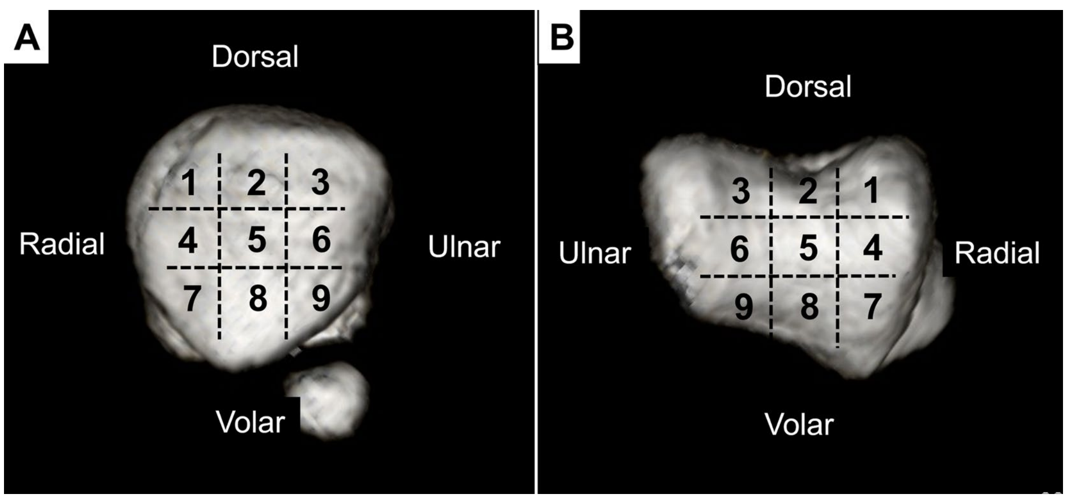

Fig. 2 Articular surfaces of the first metacarpal (**A**) and trapezium (**B**) were each divided into nine regions for analysis

the longitudinal axis of the first metacarpal shaft distal to the osteotomy and a line connecting the radial and ulnar extents of the proximal articular surface.

Clinical outcomes

Clinical outcomes were retrospectively collected from patients' medical records. Pain intensity was evaluated using a 100-mm visual analogue scale (VAS) for both resting and motion-related pain, grip strength, tip pinch strength (thumb-index finger tip-to-tip pinch), lateral pinch strength (thumb pulp to the lateral aspect of the index finger), and the Disabilities of the Arm, Shoulder, and Hand (DASH) score. These parameters were assessed both preoperatively and 1 year postoperatively.

CT imaging and analysis

CT images obtained preoperatively and 1 year postoperatively were used. For both scans, patients were positioned prone on the CT table with the examined hand extended overhead ("superman" position). The hand and wrist were stabilized using foam padding and straps, aiming to maintain a consistent, neutral position parallel to the scanner's longitudinal axis. The images were acquired using a 256-row clinical CT scanner (Revolution CT: GE Healthcare, WI, USA). Scan parameters included: field of view (FOV) 180 mm, tube voltage 120 kVp, automatic exposure control (target noise index 6), rotation time 0.5 s, and detector configuration 256×0.625 mm. Images were reconstructed with a slice thickness of 0.625 mm using a bone kernel and a 512×512 matrix, resulting in an in-plane resolution of 0.35×0.35 mm. The images were reconstructed and analyzed using commercial software (AZE Virtual Place, Canon Medical Systems, Tokyo, Japan). The articular surfaces of the first metacarpal and trapezium were divided into nine regions based on the contact areas of the subchondral bone plate identified on 3D reconstructed CT images, excluding osteophytic regions (Fig. 2). Coronal and sagittal images were reconstructed, and three-dimensional (3D) images were referenced to determine the center of each region. Using multiplanar reconstructions for guidance, circular regions of interest (ROI) with an area of 2.9 mm^2 were positioned within the subchondral cancellous bone at the center of each region, immediately beneath the hyperdense subchondral bone plate (Fig. 3). This ROI size was chosen referencing previous studies using CT-based subchondral bone density analysis in foot and ankle joints [16, 26], as a size capable of capturing the subchondral cancellous bone while averaging local variations. The HU values within these ROIs were measured. In this study, the subchondral bone plate was defined as the thin bony plate immediately deep to the calcified zone of the articular cartilage, and the subchondral bone comprised the subchondral bone plate and the underlying subchondral cancellous bone, consistent with previous definitions [27].

Arthroscopic evaluation

Arthroscopic evaluation of the CMC joint was performed in nine hands of eight patients both at initial surgery and at implant removal. Arthroscopic videos taken during these procedures were used for cartilage assessment by a single surgeon (S.I.), who was not involved in the surgeries. The International Cartilage Repair Society (ICRS)

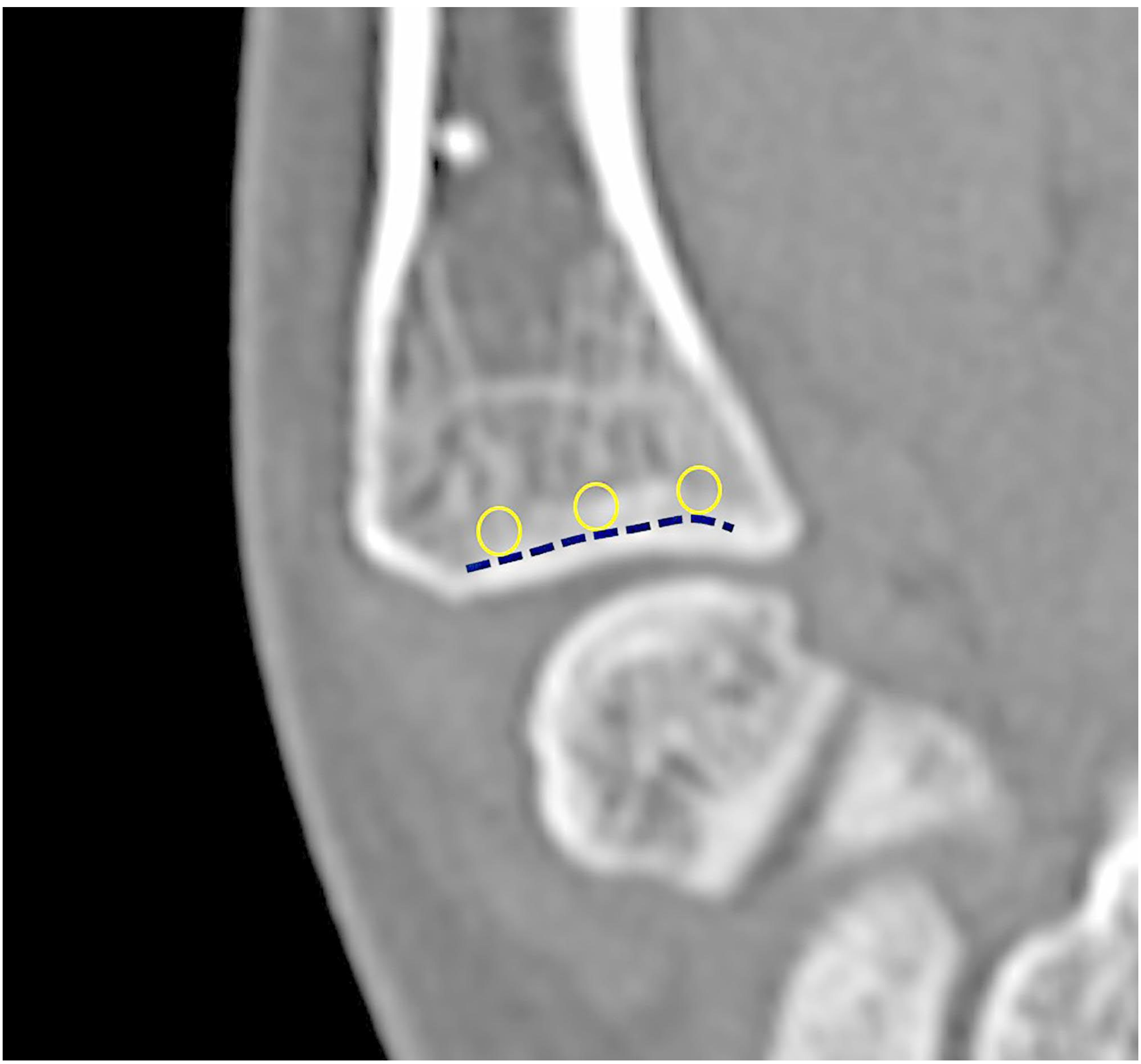

Fig. 3 Measurement of Hounsfield unit (HU) values. Regions of interest (ROI) with a 2.9 mm^2 circle set in the subchondral cancellous bone immediately beneath the subchondral bone plate in each region

Table 1 Demographic characteristics in control and osteotomy groups

	Control group	Osteotomy group	*p*-value
Age (yaers)	48.6 ± 9.4 (30–60)	57.3 ± 12.1 (30–77)	0.2675
Gender (n)	Male: 1, Female: 8	Male: 5, Female: 9	0.1778
Affected Hand	Right: 9, Left: 9	Right: 8, Left: 7	
Eaton Stage	Normal	I: 1, II: 4, III: 10	

Note: Age is presented as mean ± standard deviation (range). p-Values were calculated using the Mann-Whitney U test

grading scale was used for the assessment. Because thumb CMC cartilage is thin, approximately 0.7–0.8 mm [28], distinguishing arthroscopically between grade 2 (lesions < 50% depth) and grade 3 (> 50% depth) is challenging. Therefore, a modified grading scale grouping grades 2 and 3 together was used for this analysis to improve consistency. The modified grades were: grade 0 (normal), grade 1 (superficial lesions), grade 2/3 (partial-thickness defects not reaching bone), and grade 4 (full-thickness defects reaching subchondral bone) [29]. Similar to the CT analysis, the articular surfaces were divided into nine regions for assessment.

Statistical analysis

The Kruskal-Wallis test was used to compare the regions within the same bone, followed by the Dunn-Bonferroni test to identify specific areas with significant differences. The Wilcoxon matched-pairs signed rank test was used to compare the same regions before and after surgery. For clinical outcomes, preoperative and postoperative data were also compared using the Wilcoxon matched-pairs signed rank test. Statistical significance was set at $p < .05$.

Results

Patient demographics and clinical characteristics

The first metacarpal extension-abduction osteotomy was performed on 15 hands from 14 patients, with a control group consisting of 18 hands from nine individuals. Among the patients who underwent osteotomy, one hand was classified as Eaton grade I, four as grade II, and 10 as grade III. The mean time from surgery to CT scanning was 12.3 months (standard deviation [SD] 1.1, range 10–14), and the mean time to implant removal (for arthroscopic evaluation) was 12.8 months (SD 1.6, range 10–15). The demographic data of the participants are summarized in Table 1. Of the 15 hands included in the study, two developed severe erosion of the articular surface postoperatively, compromising the accuracy of the HU value assessment compared to the other cases. This erosion was attributed to the insertion of screws close to the joint. Therefore, postoperative HU value measurements were measured in 13 hands.

Table 2 Clinical outcomes before and after first metacarpal extension osteotomy

	Preoperative	Postoperative (one year)	*p*-value
VAS pain at rest (mm)	27.8 ± 20.3 (0–70)	4.8 ± 11.6 (0–35)	0.0010***
VAS pain during motion (mm)	68.9 ± 21.1 (42–100)	21.0 ± 21.9 (0–60)	0.0002***
Grip strength (kg)	23.9 ± 15.1 (3.5–57)	25.8 ± 16.8 (7–62)	0.504
Tip pinch strength (kg)	4.26 ± 2.91 (0.8–9.8)	4.59 ± 2.58 (1.4–9.8)	0.582
Lateral pinch strength (kg)	4.88 ± 2.38 (1.8–10)	5.58 ± 3.18 (0.8–10.8)	0.267
DASH score	30.6 ± 21.2 (0.8–64.6)	17.7 ± 16.5 (0.8–50.8)	0.0107*

Note: Variable is presented as mean ± standard deviation (range). p-values were calculated using the Wilcoxon matched-pairs signed-rank test. *$p < .05$, ***$p < .001$. VAS: Visual Analog Scale, DASH: Disabilities of the Arm, Shoulder, and Hand

Postoperative osteotomy angles

Radiographic assessment was performed pre- and postoperatively to calculate the correction angles achieved by osteotomy. On the lateral view, the volar tilt changed from a mean of 73.0° (SD 3.8°; range, 64.7°–80.0°) preoperatively to 100.0° (SD 7.5°; range, 90.0°–113.0°) postoperatively. This resulted in a mean achieved extension correction of 27.3° (SD 6.6°; range, 17.0°–35.4°). On the posteroanterior view, the first metacarpal shaft angle changed from a mean of 90.1° (SD 3.5°; range, 85.0°–98.0°) preoperatively to 98.4° (SD 4.0°; range, 94.0°–107.0°) postoperatively. This resulted in a mean achieved abduction correction of 8.3° (SD 3.8°; range, 5.2°–17.0°).

Clinical outcomes

The clinical outcomes before and after the first metacarpal extension osteotomy are summarized in Table 2. Significant improvements were observed in pain levels at rest and during motion ($p < .001$). The DASH score also showed significant improvement ($p < .05$). Although grip strength and pinch strength (tip and lateral) increased slightly, these changes were not statistically significant.

Stress distribution pattern with thumb CMC osteoarthritis

Table 3 presents the HU values for each region in the control group and in the preoperative and postoperative patients.

In the control group, HU values for the first metacarpal region 3 (dorso-ulnar) were significantly lower compared to regions 4 (central-radial), 5 (central), and 8 (central-palmar) (Fig. 4A). Conversely, patients with thumb CMC osteoarthritis exhibited significantly higher HU values in the palmar regions (7, 8, and 9) than in the dorsal regions (1, 2, and 3) (Fig. 4B). The trapezium in the control group showed no significant differences between

Table 3 HU values of the first metacarpal bone and trapezium in the thumb CMC joint: comparison between control, preoperative, and postoperative groups

The First Metacarpal			
Area	**Control**	**Thumb CMC Osteoarthritis Pre-operative**	**Thumb CMC Osteoarthritis Post-operative**
1	478.0 (386.8-550.5)	166 (115–213)	191 (162–316)
2	427.2 (345.0-480.8)	212 (110–389)	309 (220–368)
3	406.1 (360.9-477.6)	239 (128–359)	330 (227–356)
4	543.9 (446.6-618.8)	369 (291–486)	359 (253–446)
5	533.7 (423.8-613.4)	423 (374–518)	339 (288–442)
6	471.0 (422.0-564.2)	421 (292–466)	348 (315–408)
7	514.8 (364.2-549.5)	651 (597–747)	403 (350–493)
8	560.7 (480.9-613.3)	758 (643–803)	433 (307–475)
9	494.5 (447.8-627.3)	694 (544–777)	404 (272–477)
The Trapezium			
Area	**Control**	**Thumb CMC Osteoarthritis Pre-operative**	**Thumb CMC Osteoarthritis Post-operative**
1	572.8 (503.6-644.3)	538 (420–661)	413 (346–582)
2	629.2 (473.8-793.5)	596 (550–640)	469 (428–489)
3	575.6 (472.9–733.0)	473 (382–537)	389 (331–455)
4	553.8 (424.8-613.7)	791 (632–1000)	442 (361–512)
5	732.5 (526.6-794.2)	898 (867–960)	571 (508–649)
6	613.8 (514.2-672.6)	772 (696–824)	517 (490–530)
7	521.1 (450.9-590.5)	590 (425–678)	459 (397–571)
8	555.1 (488.6-661.6)	526 (415–660)	398 (361–518)
9	490.9 (451.3-561.2)	410 (359–468)	433 (272–499)

Note: HU, Hounsfield unit; CMC, carpometacarpal. Values are presented as median (interquartile range)

regions (Fig. 5A). However, in patients with thumb CMC osteoarthritis, regions 4 (central-radial), 5 (central), and 6 (central-ulnar) had significantly higher HU values compared to the palmar and dorsal regions (Fig. 5B).

Changes in stress distribution after osteotomy

A comparison of HU values of each region before and after surgery revealed changes in stress distribution (Fig. 6). The palmar regions (7, 8, and 9) of the first metacarpal, which had high preoperative HU values, decreased significantly after surgery. Although regions 7 and 8 (central-palmar and palmo-radial) remained higher than region 1 (dorso-radial), the stress distribution became more uniform, with dispersed high-stress areas (Fig. 4C). In the trapezium, the dorsal (2, 3) and central regions (4, 5, and 6) decreased postoperatively, resulting in a more uniform stress distribution throughout the entire articular surface (Fig. 5C). Representative HU value maps are shown in Fig. 7.

Arthroscopic evaluation

Before osteotomy, the articular cartilage on the metacarpal side was graded as 4, indicating exposure of the subchondral bone in all but one hand. On the trapezium side, subchondral bone was exposed (grade 4) in all the cases. One year postoperatively, improvements in the overall ICRS grade were observed in five hands on the metacarpal side and in four hands on the trapezium side (Fig. 8). Improvement typically involved a change from grade 4 to grade 2/3, suggesting coverage of the exposed bone with repair tissue. A heat map detailing the cartilage evaluation for each region using the modified grading (0, 1, 2/3, 4) is shown in Fig. 9. Representative images show repair of the articular surface after surgery (Fig. 10).

Discussion

This study demonstrated two main findings regarding the effect of first metacarpal extension-abduction osteotomy on thumb CMC osteoarthritis. Firstly, the osteotomy

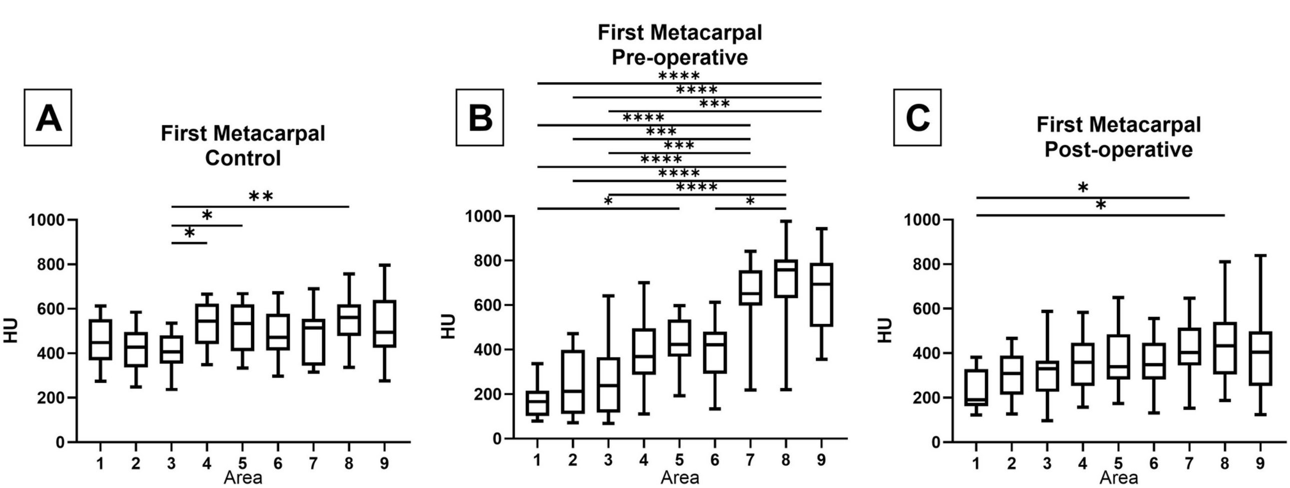

Fig. 4 Hounsfield unit (HU) values for each region of the first metacarpal in the (**A**) control group, (**B**) preoperative thumb carpometacarpal osteoarthritis patients, and (**C**) postoperative patients. In thumb carpometacarpal osteoarthritis, high stress concentrates on the palmar aspect of the first metacarpal, becoming more evenly distributed after osteotomy. Data are presented as box-and-whisker plots. Significance levels determined by the Kruskal-Wallis test are indicated as **P* <.05, ***P* <.01, ****P* <.001, *****P* <.0001

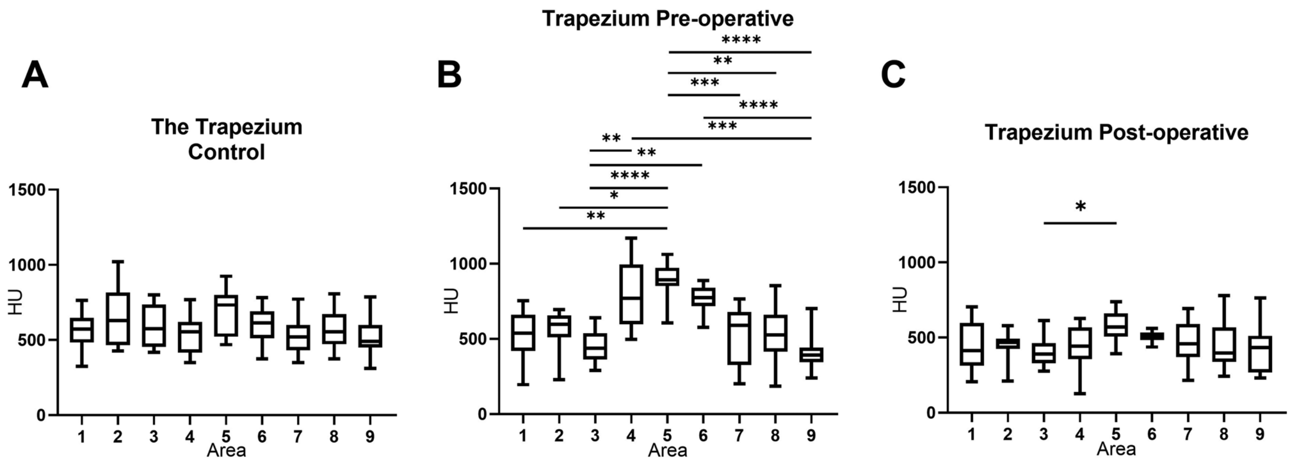

Fig. 5 Hounsfield unit (HU) values for each region of the trapezium in the (**A**) control group, (**B**) preoperative thumb carpometacarpal osteoarthritis patients, and (**C**) postoperative patients. In thumb carpometacarpal osteoarthritis, high stress concentrates on the central regions of the trapezium, becoming more evenly distributed after osteotomy. Data are presented as box-and-whisker plots. Significance levels determined by the Kruskal-Wallis test are indicated as **P*<.05, ***P*<.01, ****P*<.001, *****P*<.0001

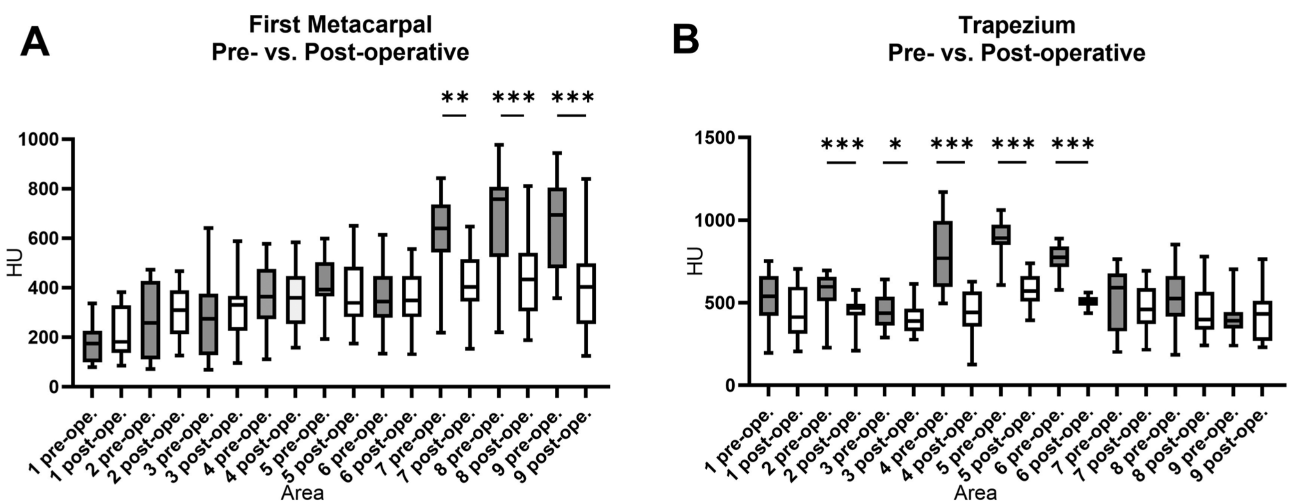

Fig. 6 Changes in Hounsfield unit (HU) value before and after surgery for each region of the first (**A**) metacarpal and (**B**) trapezium. Gray bars represent preoperative values, and white bars represent postoperative values. Data are presented as box-and-whisker plots. Significance levels determined by the Wilcoxon rank-sum test are indicated as **P*<.05, ***P*<.01, ****P*<.001

altered the stress distribution pattern in the CMC joint, preoperatively dispersing the high-stress areas that were concentrated on the palmar side of the first metacarpal and the central regions of the trapezium. Secondly, arthroscopic evaluation revealed improvements in articular cartilage grade 1 year postoperatively, suggesting that a cartilage-like tissue regenerates on the previously exposed subchondral bone surface. These findings provide new insights into the mechanisms underlying the clinical benefits of first metacarpal osteotomy for thumb CMC osteoarthritis and support its role as an effective joint-preserving surgery. Our results suggest that this procedure holds the potential to delay or avoid the need for joint-sacrificing surgeries, such as arthroplasty or arthrodesis, even in patients with more advanced stages of the disease.

The preoperative stress distribution observed in our study, with higher stress on the palmar aspect of the metacarpal and the central regions of the trapezium, is consistent with previous reports evaluating the distribution of subchondral bone density in the CMC joint under physiological loading conditions [21]. Furthermore, our results demonstrate that the load redistribution following osteotomy, previously reported in cadaver studies, can be reproduced as changes in stress distribution under physiological loading conditions 1 year postoperatively [13–15]. The relationship between abnormal subchondral bone remodeling, sclerotic changes, and pain in osteoarthritis is well-documented [30]. These findings suggest

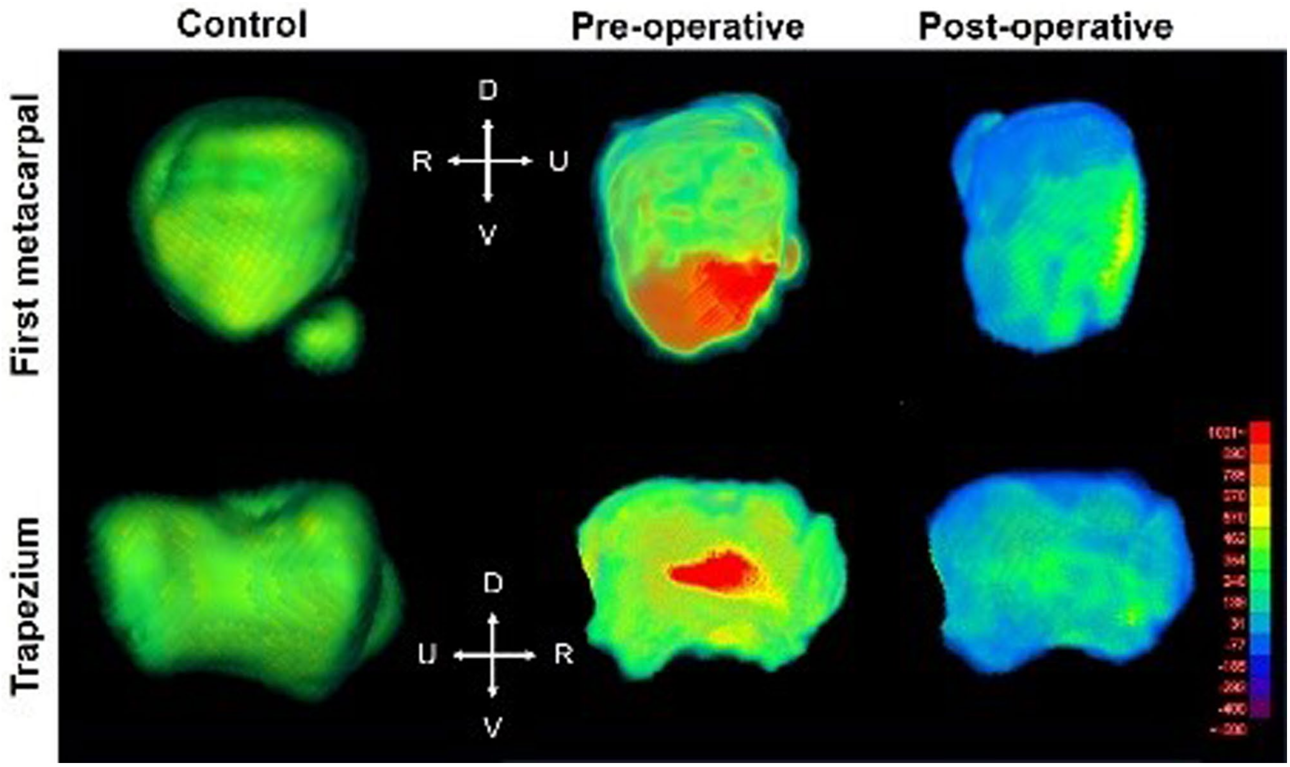

Fig. 7 Hounsfield unit (HU) value mapping of representative cases. The control group is a 38-year-old woman with uniform HU values in both the first metacarpal and trapezium. HU value mapping of a 47-year-old man with Eaton stage III thumb carpometacarpal osteoarthritis before and after surgery. The high-stress areas indicated in red preoperatively become more uniform postoperatively

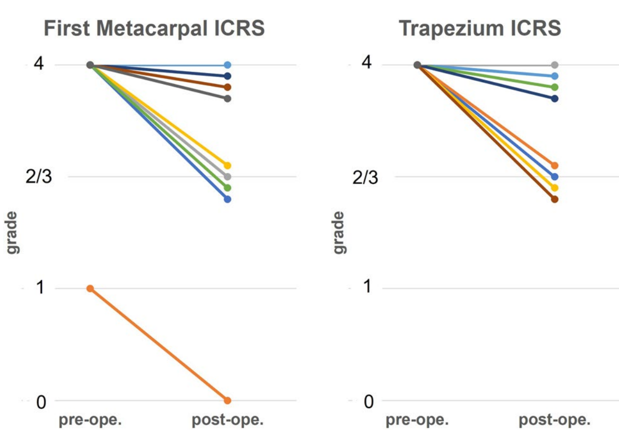

Fig. 8 Changes in the International Cartilage Repair Society (ICRS) grading scale before and after surgery for the first metacarpal and trapezium. Approximately half of the cases showed improvement in the grade for both the first metacarpal and trapezium

that this procedure may contribute to the long-term clinical benefits by altering stress distribution.

Arthroscopic evaluation of the thumb CMC joint after the first metacarpal osteotomy has not been previously reported. Joint remodeling and cartilage repair after osteotomy for osteoarthritis have been frequently reported in other joints, such as the knee and ankle [22–24]. Studies have shown that osteotomy procedures in these joints can lead to stress redistribution and subsequent cartilage repair, with some reports even suggesting the formation of hyaline-like cartilage resembling the original tissue [24]. Although our study provides evidence of articular cartilage improvement based on arthroscopic evaluation, particularly evident in patients with Eaton stage III disease (which comprised the majority of our cohort), mostly from grade III, it did not show regeneration of healthy cartilage tissue. Additionally, histological analyses were not performed to confirm the nature of the regenerated tissues. Further research, including histological studies, is needed to better understand the extent and quality of cartilage repair following the first metacarpal osteotomy in the thumb CMC joint.

The osteotomy angles used in this study, 30° extension and 10° abduction, were chosen based on existing literature and biomechanical considerations. Since Wilson first proposed a 20–30° extension osteotomy [3], numerous studies, including biomechanical analyses, have reported favorable outcomes with extension angles ranging from 15° to 30° [4, 5, 8–15, 31]. In thumb CMC osteoarthritis, progression of the disease often involves dorsal and radial subluxation of the first metacarpal, leading to erosion of the palmar (ulnar-palmar) articular surface [13, 14]. Adding abduction to the extension osteotomy aims to optimize pinch grip position and joint contact, and good

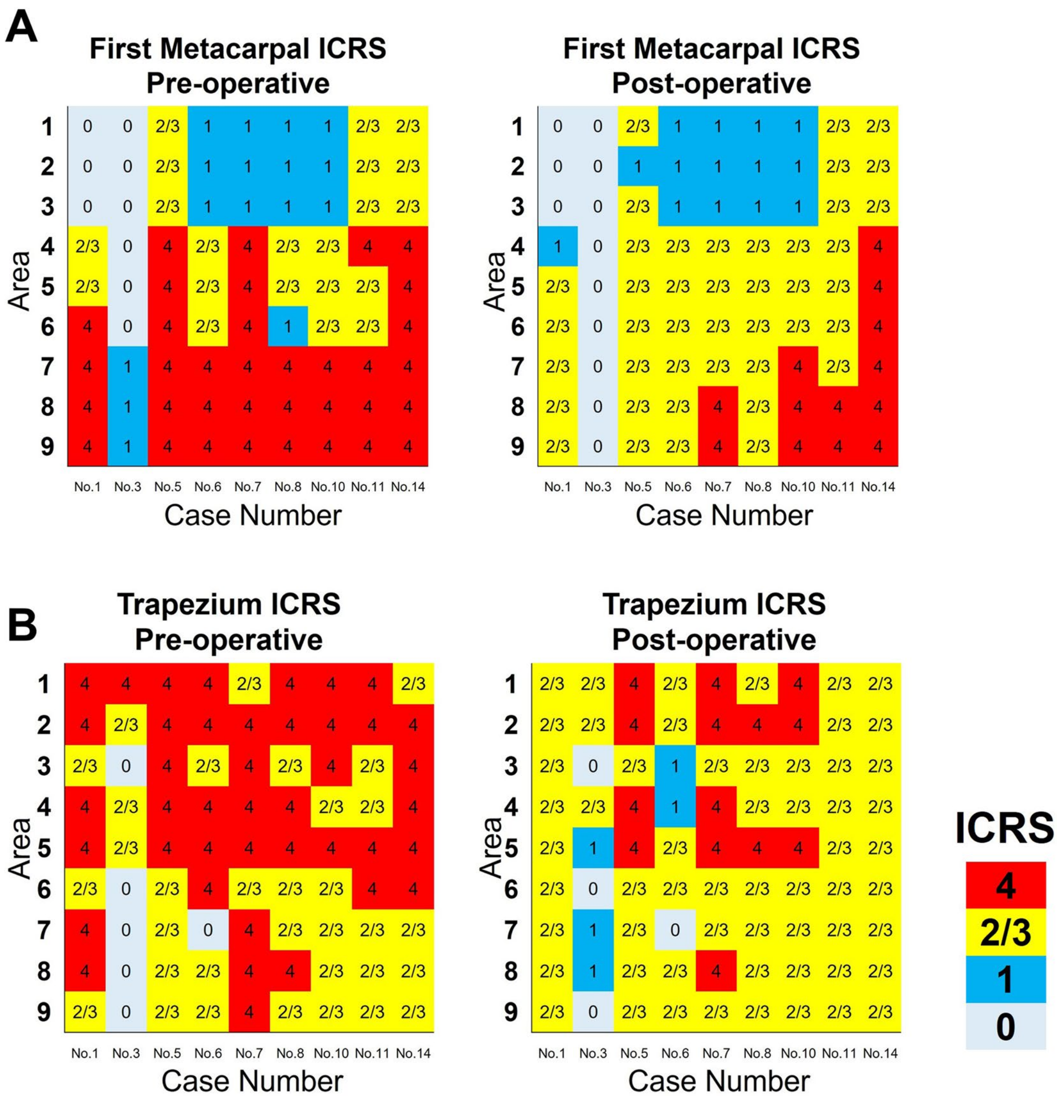

Fig. 9 Heat map of the International Cartilage Repair Society (ICRS) grades for each region of the articular surfaces of the first metacarpal and trapezium in nine cases that underwent arthroscopic evaluation before and after surgery. Improvements in grade were observed in the high-stress areas on the palmar aspect of the first metacarpal and the dorsal and central regions of the trapezium. Grade 4: red, grade 2/3: yellow, grade 1: light blue, grade 0: gray

results have been reported when combining abduction with extension [6, 8, 32, 33]. Based on these reports, we performed an osteotomy with 10° abduction in addition to extension, intending to further enhance joint congruity. Our findings of postoperative stress redistribution support the effectiveness of this combined osteotomy, although the precise contribution of the 10° abduction requires further investigation.

Our findings have significant implications for managing thumb CMC osteoarthritis, particularly in the advanced stages of the disease. Previous cadaver studies have suggested that first metacarpal osteotomy may not effectively alter the load center in end-stage osteoarthritis [13]. However, our study demonstrated that stress distribution could become more uniform after osteotomy, even in patients with Eaton stage III disease, which constituted 68.7% of our study population. This discrepancy could be attributed to the differences between cadaveric and physiological loading conditions. Moreover, good clinical outcomes have been reported following the first metacarpal osteotomy in patients with Eaton stage III osteoarthritis [31]. As a joint-preserving procedure, the first metacarpal osteotomy maintains the option for future joint reconstruction surgeries. Although this procedure has traditionally been indicated for early-stage osteoarthritis (Eaton stages I and II) and younger patients, our findings suggested that it might also be applicable to more advanced stages of the disease.

While this study demonstrated improvements in clinical outcomes such as pain and DASH scores, correlating

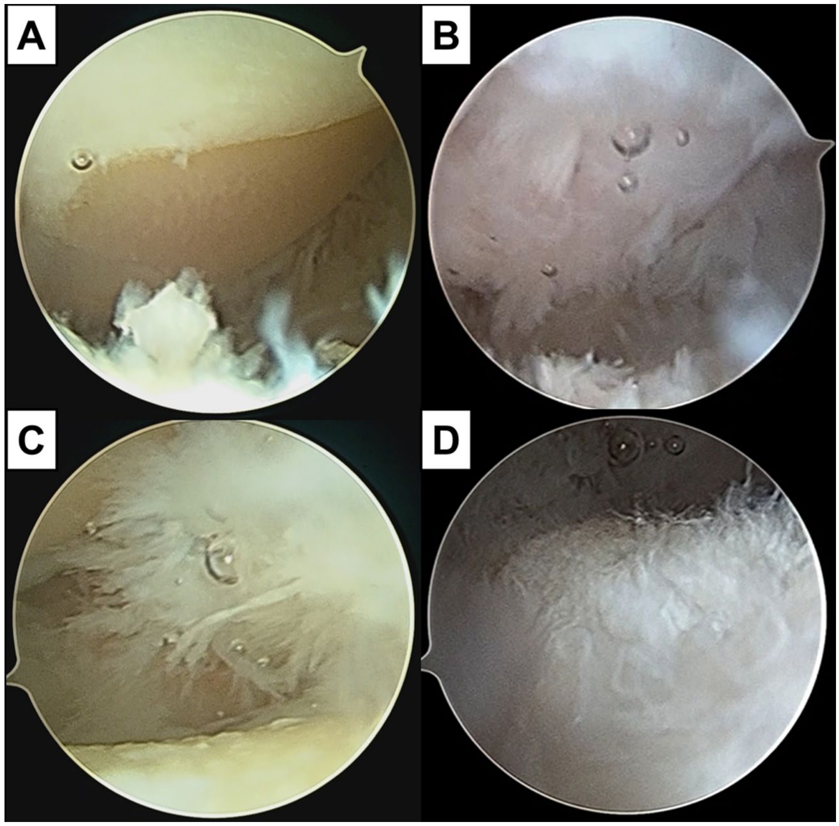

Fig. 10 Arthroscopic findings of the thumb carpometacarpal joint. (**A**) Preoperative arthroscopic view of a 47-year-old man with Eaton stage III osteoarthritis showing exposed subchondral bone (International Cartilage Repair Society [ICRS] grade 4) on the palmar aspect of the first metacarpal. (**B**) At 1 year postoperatively, the subchondral bone was covered with fibrocartilage (ICRS grade 2/3). (**C**) Preoperative view showing exposed subchondral bone (ICRS grade 4) in the central region of the trapezium. (**D**) At 1 year postoperatively, the subchondral bone was covered with fibrocartilage (ICRS grade 2/3)

these improvements directly with the observed changes in stress distribution (HU values) or arthroscopic findings on an individual basis proved challenging due to the limited sample size. Future studies should aim to investigate this relationship more rigorously, potentially identifying imaging or arthroscopic markers that predict clinical response to osteotomy.

This study has several limitations. Firstly, the sample size was relatively small, and the results were influenced by the surgeon's selection bias in choosing the surgical method. Further research is needed to establish clear indications for a first metacarpal osteotomy. Secondly, the follow-up period of one year allows assessment of relatively early remodeling but does not provide insight into the long-term durability of the observed changes. Thirdly, bone mineral density, which could affect HU values of the subchondral bone, was not evaluated. Although none of the patients in our study were receiving treatment for osteoporosis, high HU values might reflect sclerotic bone changes and variations in bone mineral density. Therefore, we did not directly compare the HU values between the control group and the pre-osteotomy group. Fourthly, the relationship between HU values and histological changes in the articular cartilage remained unclear. Subchondral bone plays a crucial role in maintaining articular cartilage homeostasis, and the condition of the subchondral bone has been reported to directly influence cartilage degeneration [34, 35]. Moreover, a sclerosed subchondral bone plate observed on CT has been linked to histological degenerative changes in the articular cartilage [36]. However, further research is needed to determine whether improvements in HU values translate to cartilage improvement. Fifthly, phantom calibration was not performed for the HU measurements in this study. Phantom calibration enables the standardization and comparison of absolute bone density values across different scanners or between groups. While the superficial location and small size of the thumb CMC joint likely minimize variability from beam hardening effects, the absence of phantom calibration led us to focus our analysis on intra-individual changes (preoperative vs. postoperative using paired tests) and relative distribution patterns, rather than direct comparisons of absolute HU values between groups. Lastly, the postoperative CT scans were performed before plate removal, which could introduce metal artifacts. The CT scanning system used in this study incorporated a built-in artifact reduction feature. Although this artifact correction is reported to have high accuracy, it has also been reported to potentially lower HU values by a few percent [37, 38]. Therefore, the possibility that the overall postoperative HU values were lowered due to this effect cannot be entirely excluded. However, the observation that the abnormal stress distribution pattern became more uniform after surgery suggests that the biological effect of stress redistribution was predominant.

Conclusions

This study demonstrated that the first metacarpal extension-abduction osteotomy led to the remodeling of the thumb CMC joint, transforming the irregular stress distribution across the articular surfaces towards a more normal pattern. Furthermore, arthroscopic evaluation suggested a potential for articular cartilage repair following the osteotomy. These findings provide new insights into the mechanisms underlying the clinical benefits of the first metacarpal osteotomy and support its use as a joint-preserving procedure for treating thumb CMC osteoarthritis, even in more advanced stages of the disease. Future research should focus on larger-scale investigations with longer follow-up periods to elucidate the relationship between clinical outcomes, HU values, and cartilage repair. These comprehensive studies are likely to lead to the determination of true indications for this osteotomy procedure, ultimately optimizing patient selection and improving long-term treatment outcomes.

Abbreviations

CMC	Carpometacarpal
CT	Computed tomography
HU	Hounsfield units
ICRS	International Cartilage Repair Society
VAS	Visual analogue scale
DASH	Disabilities of the Arm, Shoulder, and Hand
3D	Three-dimensional
ROI	Regions of interest
SD	Standard deviation

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Author contributions

S.I contributed to evaluate the CT data and write the manuscript. A.K. performed surgeries and other treatments, conceptualized and designed the study and revised the manuscript. T.T. conducted CT and clinical evaluation. K.Y. performed CT image analysis. M.M. and Y.S. assisted the data collection. N.A. supervised the project and revised the manuscript. All the authors have read and approved the final version of the manuscript.

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Data availability

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at Hiroshima university.

Declarations

Ethics approval and consent to participate

This study was approved by the ethics committee of Hiroshima University (approval number: E-2344). All methods were performed in accordance with the Declaration of Helsinki and the relevant guidelines and regulations. Informed consent was obtained from all individual participants included in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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