

A biomechanical analysis of the effect of hydroxyapatite augmentation for trochanteric femoral fractures

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Abstract. Hydroxyapatite (HA) augments are used to treat trochanteric femoral fractures. However, the efficacy of HA augmentation has not been fully described in trochanteric femoral fracture surgery. In total, 85 patients were enrolled in the present study; all had trochanteric femoral fractures between January 2016 and October 2020, 45 with HA (HA group) and 40 without HA (N group). The intraoperative lag screw insertion torque was directly measured and the amount of lag screw telescoping with and without HA augmentation after surgery was analyzed. Maximum lag screw insertion torque (max-torque), bone mineral density in the opposite femoral neck (n-BMD), tip apex distance (TAD) of the lag screw, radiographic findings including fracture union, the amounts of lag screw telescoping and occurrence of complications were evaluated. A total of 12 patients were excluded if they were aged under 60 years old, had ipsilateral surgery and disorders in the hip joint, TAD of the lag screw ≥ 26 mm on postoperative radiographs and had measurement errors. A total of 73 fractures could be analyzed: HA group (n=36) and N group (n=37). Max-torque/n-BMD ratios were higher in the HA group compared with in the N group (7.23 ± 2.71 vs. 5.93 ± 1.91 g/cm²·N·m; $P=0.04$). The amounts of lag screw telescoping in the HA group were smaller compared with the N group (1.41 ± 2.00 vs. 2.58 ± 2.34 ; $P=0.05$). Evaluation

of screw insertion torque showed maximum screw insertion torque correlated well with n-BMD in both groups, HA ($R=0.57$; $P<0.01$) and N group ($R=0.64$; $P<0.01$). No correlation was found between maximum screw insertion torque and TAD in both groups, HA ($R=-0.10$; $P=0.62$) and N group ($R=0.02$; $P=0.93$). All fractures were radiographically united without any complications. These results support the effectiveness of HA augmentation, indicating higher resistance against rotational instability and reduced lag screw telescoping in trochanteric femoral fracture treatment.

Introduction

The incidence of trochanteric femoral fractures has increased owing to an aging society (1). Falling is one of the main causes of fracture. Hydroxyapatite (HA) augments are used to treat trochanteric femoral fractures. However, the efficacy of HA augmentation has not been fully described in trochanteric femoral fracture surgery. In total, 85 patients were enrolled in the present study; all had trochanteric femoral fractures between January 2016 and October 2020, 45 with HA (HA group) and 40 without HA (N group). The intraoperative lag screw insertion torque was directly measured and the amount of lag screw telescoping with and without HA augmentation after surgery was analyzed. Maximum lag screw insertion torque (max-torque), bone mineral density in the opposite femoral neck (n-BMD), tip apex distance (TAD) of the lag screw, radiographic findings including fracture union, the amounts of lag screw telescoping and occurrence of complications were evaluated. A total of 12 patients were excluded if they were aged under 60 years old, had ipsilateral surgery and disorders in the hip joint, TAD of the lag screw ≥ 26 mm on postoperative radiographs and had measurement errors. A total of 73 fractures could be analyzed: HA group (n=36) and N group (n=37). Max-torque/n-BMD ratios were higher in the HA group compared with in the N group (7.23 ± 2.71 vs. 5.93 ± 1.91 g/cm²·N·m; $P=0.04$). The amounts of lag screw telescoping in the HA group were smaller compared with the N group (1.41 ± 2.00 vs. 2.58 ± 2.34 ; $P=0.05$). Evaluation of screw insertion torque showed maximum screw insertion torque correlated well with n-BMD in both groups, HA

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Abbreviations: HA, hydroxyapatite; n-BMD, bone mineral density in the opposite femoral neck; TAD, tip apex distance; LOWESS, locally weighted scatterplot smoothing

Key words: hydroxyapatite, trochanteric femoral fractures, lag screw augmentation

($R=0.57$; $P<0.01$) and N group ($R=0.64$; $P<0.01$). No correlation was found between maximum screw insertion torque and TAD in both groups, HA ($R=-0.10$; $P=0.62$) and N group ($R=0.02$; $P=0.93$). All fractures were radiographically united without any complications. These results support the effectiveness of HA augmentation, indicating higher resistance against rotational instability and reduced lag screw telescoping in trochanteric femoral fracture treatment.

and is related to high mortality rates (2,3). Open reduction and internal fixation using an intramedullary nail is the most commonly used operative method for fractures (4). Many implant designs and augmentation methods have been reported to increase the initial fixation strength (5,6). However, complications such as necrosis of the femoral head and cut-out of the lag screw are problematic due to lower bone mineral density (BMD) (7,8). The uses of cement augmentation involve fixation of the femoral head screw (9,10). While cement augmentation reportedly increases the lag screw fixation force (11,12), cement usage is a risk factor for femoral head necrosis due to the chemical and heat reactions (9,13-16). Hydroxyapatite (HA) augmentation has the advantage of high biomechanical and biochemical stability after implantation. HA augmentation is widely used in the treatment of trochanteric femoral fracture, distal radial fracture, proximal tibial fracture, and spinal surgery (17,18). HA augmentation reportedly increases peri-implant bone formation after surgery and demonstrates increased cut-out resistance (17,19,20). In this study, Neobrace® (Neobrace®, Aimedica MMT Co., Ltd., Japan) was used for HA augmentation. This is a cylinder-shaped implant with a length of 25 mm, inner diameter of 3.5 mm, and outer diameter of 7 mm (Fig. 1A). Neobrace® is composed of pure HA particles with a porosity of 72-78% and a diameter of 150-200 μm . Neobrace® was easily collapsed by lag screw insertion into comminuted granules and was scattered around the screws (Fig. 1B). The granule size was 40-70 μm , which was sufficiently strong (12-18 MPa). HA granules have advantages such as high biocompatibility, as HA is the main composite of bone.

Evaluation of the postoperative risk of lag screw cut-out during surgery is difficult. It has been reported that the insertion torque of the screw is a key predictor for evaluating the cut-out resistance force (21-23). Local BMD [e.g. BMD around femoral neck (n-BMD)] and force at cut-out are highly correlated with maximum screw insertion torque (21-23). Thus, we calculated max-torque/n-BMD ratio because this would be a good surrogate parameter to indicate bone strength. Moreover, it indicates that max-torque/n-BMD ratio should be statistically similar to each other compared to each specimen. Our previous study showed that the mean lag screw insertion torque (mean torque)/screw insertion and n-BMD increased with the use of a HA tube in the treatment of trochanteric femoral fractures (24). However, the maximum lag screw insertion torque (max-torque)/n-BMD did not reach significance as noise in the raw data made statistical analysis difficult. The purpose of this study was to investigate the effectiveness of HA augmentation in the treatment of trochanteric femoral fractures using novel data-smoothing techniques. We measured the lag screw insertion torque and n-BMD with and without HA augmentation during the surgery and subsequently evaluated the effects of HA augmentation on max-torque/n-BMD. Moreover, the

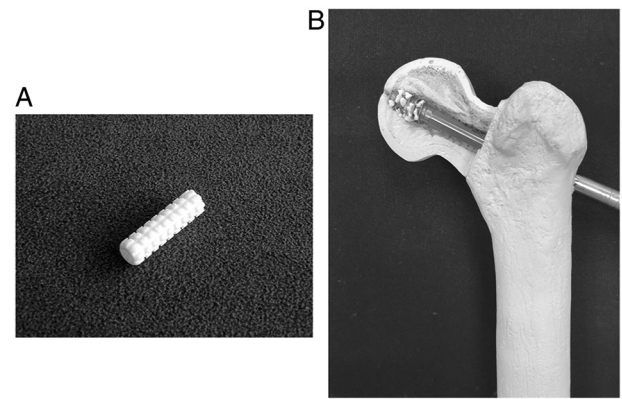


Figure 1. (A) HA tube. (B) HA tube was crushed and scattered around the lag screw in a model bone. HA, hydroxyapatite.

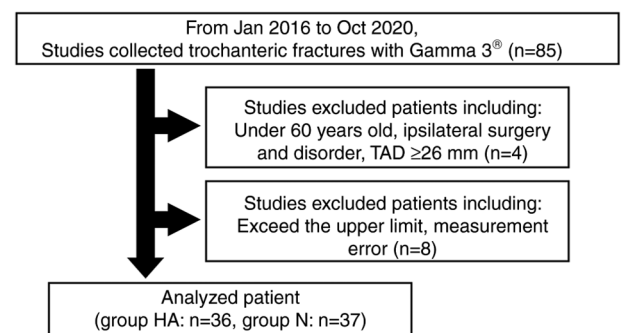


Figure 2. Overview of the selection of patients. HA, hydroxyapatite; N, without HA; TAD, tip apex distance of the lag screw.

amount of lag screw telescoping with and without postoperative HA augmentation was evaluated.

Materials and methods

Patients' selection and exclusion. This study was approved by the Research Ethics Committee of Kainan Hospital. Written informed consent was obtained from all participants before surgery. Between January 2016 and October 2020, 85 patients with closed trochanteric femoral fractures treated using Gamma3® (Stryker, MI, USA) were enrolled in the study. The mean age of all patients was 83.8 ± 8.4 years (median, 84; range, 54-102). A tip apex distance (TAD)-the distance from the apex of the femoral head to the tip of the lag screw on anteroposterior and lateral radiographs-greater than 25 mm identified the risk for cut-out (25,26). Therefore, patients were excluded if they were aged less than 60 years, had ipsilateral surgery and disorders in the hip joint, and TAD of the lag screw ≥ 26 mm on postoperative radiographs (Fig. 2).

Measurement method and data analysis. Surgery was conducted under lumbar or general anesthesia. In the HA group, we used 2 Neobrace® before lag screw insertion via the lag screw hole (Fig. 1). The lag screw insertion torque was obtained continuously using a digital torque measurement device (HTGS-5N, 10N, Imada Co., Ltd., Tokyo, Japan), and the data were recorded using the software (Force Recorder,

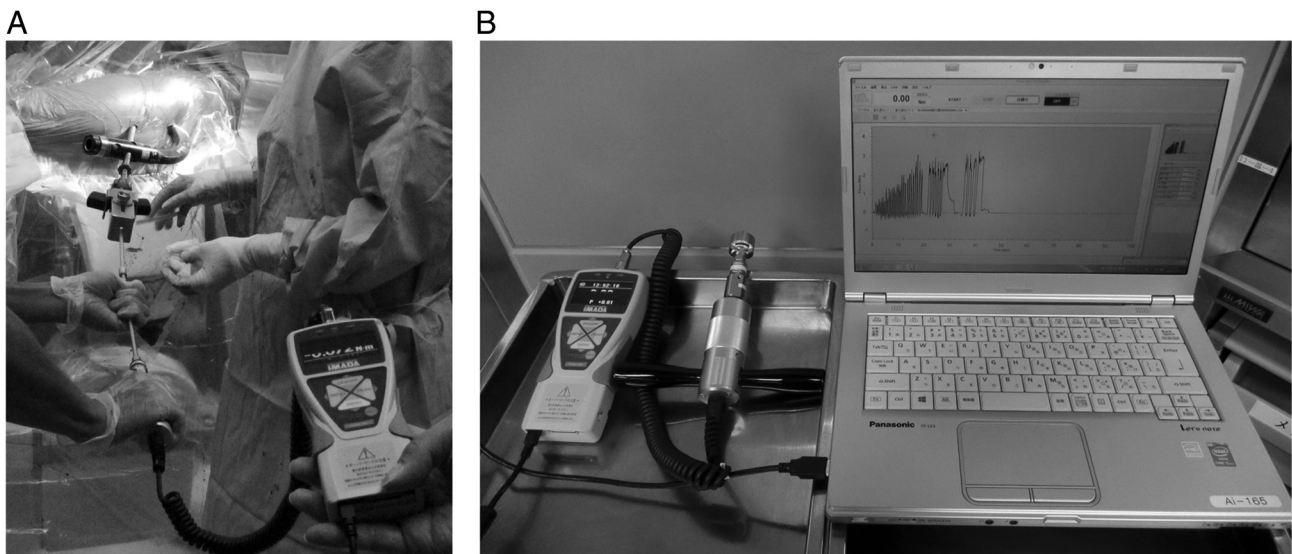


Figure 3. (A) The examination system connected to the lag screw handle and a laptop computer. (B) Intraoperative examination picture showing the lag screw inserted through the torque-measuring device.

Imada Co., Ltd., Japan) (Fig. 3). The sampling rate was 2,000 Hz. The lag screw was manually inserted using a digital torque measurement device connected to a screwdriver. Data were excluded if the measurements exceeded the upper limit and had measurement error (Fig. 2). The data were described as time-series scatterplots with noise, and the locally weighted scatterplot smoothing (LOWESS) technique was adopted to smooth the data series in this study (27). The library and application programming interface, including *NumPy*, *SciPy*, and *statsmodels.api*, were imported into Python (Python Software Foundation, Wilmington, USA). The function *statsmodels.nonparametric.smoothers_lowess.lowess* was used to smoothen the data series (parameter: *frac*=0.01). This method enabled the visualization of numerous data series of torque. As previously described, a normal graph of the screw insertion torque exhibits a plateau torque pattern followed by a clear peak (27). Thus, we excluded data that had no exact plateau and/or peak and exceeded the upper limit of the torque gauge in this study. The function *scipy.signal.find_peaks* was used to obtain the peak of the smoothed data (parameters: *height*=0.3, *distance*=500). The highest peak of lag screw insertion torque was defined as the max-torque.

The n-BMD was calculated using a dual-energy X-ray absorptiometry (DEXA) machine (DCS-900EX, Hitachi, Ltd., Tokyo, Japan). TAD of the lag screw was measured on post-operative radiographs at the final follow-up. Radiographical evidence of fracture union and postoperative complications was also assessed at the final follow-up. The amount of lag screw telescoping and radiographic evidence of fracture union at the final follow-up were evaluated by a single surgeon.

Statistical analysis. Both categorical and continuous variables including patients' age, sex, operative side, follow-up duration, n-BMD, max-torque/n-BMD, TAD of the lag screw, amount of lag screw telescoping, radiographical evidence of fracture union, and complications were evaluated using Fisher's exact test and Welch's t-test. Pearson's correlation and overall agreement were calculated to assess the reliability of each

parameter, including max-torque, n-BMD, and TAD, in the two groups. Statistical analysis was conducted using the R statistical package, version 4.0.4 (R Core Team, Foundation for Statistical Computing, Austria). All reported two-sided P-values were evaluated, and P-values <0.05 were considered statistically significant.

Results

Among the 85 patients enrolled, 12 patients were excluded (Fig. 2). Thus, a total of 73 patients (patients with the use of HA augments: HA group, n=36; patients without the use of augments: N group, n=37) were analyzed in the study. The mean age of participants was 83.4 ± 7.9 years (range, 63-95) in the HA group and 85.7 ± 7.7 years (range, 67-107) in the N group ($P=0.22$). There were 10 males and 26 females in the HA group and 8 males and 29 females in the N group ($P=0.60$). Operative sides of the HA and N groups were 18 right and 18 left sides and 20 right and 17 left sides, respectively ($P=0.82$). The follow-up durations were 11.88 ± 14.56 months (range, 0.23-62.00) in the HA group and 9.87 ± 13.14 months (range, 0.20-12.00) in the N group ($P=0.54$). n-BMD was 0.45 ± 0.11 g/cm² (range, 0.25-0.64) in the HA group and 0.48 ± 0.13 g/cm² (range, 0.25-0.86) in the N group ($P=0.26$).

Max-torque was 3.26 ± 1.49 N·m (range, 1.08-8.50) in the HA group and 2.76 ± 1.16 N·m (range, 0.92-6.03) in the N group ($P=0.11$). Max-torque/n-BMD was 7.23 ± 2.71 g/cm²·N·m (range, 2.51-13.26) in the HA group and 5.93 ± 1.91 g/cm²·N·m (range, 3.29-12.25) in the N group ($P=0.04$). TAD was 18.89 ± 4.38 mm (range, 9.11-25.82) in the HA group and 18.32 ± 3.72 mm (range, 10.70-25.16) in the N group ($P=0.60$). The amounts of lag screw telescoping was 1.41 ± 2.00 mm (range, 0-8.81) in the HA group and 2.58 ± 2.34 mm (range, 0-7.47) in the N group ($P=0.05$) (Table I).

Regarding the relationships between the max-torque and n-BMD, the values of correlation coefficients were 0.57 in the HA group ($P<0.01$) and 0.64 in the N group ($P<0.01$). In the relationship between the max-torque and TAD, the values

Table I. Overview of preoperative variables in the HA and N groups.

| Preoperative variables | HA group (n=36) | N group (n=37) | P-value |
|--------------------------------------------------|--------------------------|--------------------------|-------------------|
| Age, years (range) | 83.4±7.93 (63-95) | 85.7±7.70 (67-107) | 0.22 |
| Sex | | | 0.60 |
| Male | 10 | 8 | |
| Female | 26 | 29 | |
| Side | | | 0.82 |
| Right | 18 | 20 | |
| Left | 18 | 17 | |
| Follow-up duration, months (range) | 11.88±14.56 (0.23-62.00) | 9.87±13.14 (0.20-12.00) | 0.54 |
| n-BMD, g/cm ² (range) | 0.45±0.11 (0.25-0.64) | 0.48±0.13 (0.25-0.86) | 0.26 |
| Max-torque, N·m (range) | 3.26±1.49 (1.08-8.50) | 2.76±1.16 (0.92-6.03) | 0.11 |
| Max torque/n-BMD, g/cm ² ·N·m (range) | 7.23±2.71 (2.51-13.26) | 5.93±1.91 (3.29-12.25) | 0.04 ^a |
| TAD, mm (range) | 18.89±4.38 (9.11-25.82) | 18.32±3.72 (10.70-25.16) | 0.60 |
| Telescoping, mm (range) | 1.41±2.00 (0-8.81) | 2.58±2.34 (0-7.47) | 0.05 |
| Complications | N/A | N/A | |

^aP<0.05. HA, hydroxyapatite; N, without HA; n-BMD, bone mineral density of the uninjured opposite side of femoral neck; Max-torque, maximum screw insertion torque; TAD, tip apex distance of the lag screw; N/A, not applicable.

Table II. Pearson's correlation and overall agreement between max-torque and n-BMD and TAD.

| Variables | Correlation | Lower limit | Upper limit | P-value |
|-----------|-------------|-------------|-------------|--------------------|
| n-BMD | | | | |
| HA group | 0.57 | 0.26 | 0.77 | <0.01 ^a |
| N group | 0.64 | 0.37 | 0.81 | <0.01 ^a |
| TAD | | | | |
| HA group | -0.10 | -0.45 | 0.28 | 0.62 |
| N group | 0.02 | -0.35 | 0.38 | 0.93 |

^aP<0.05. HA, hydroxyapatite; N, without HA; n-BMD, bone mineral density of the uninjured opposite side of femoral neck; Max-torque, maximum screw insertion torque; TAD, tip apex distance of the lag screw.

of the correlation coefficients were -0.10 in the HA group (P=0.62) and 0.02 in the N group (P=0.93) (Table II). All fractures were radiographically united without any complications.

Discussion

In this study, we examined the mechanical effects of HA augmentation in the treatment of trochanteric femoral fractures. Our analyses identified a significantly positive relationship between max-torque and BMD with and without HA augmentation. Our previous study demonstrated that lag screw insertion torque was related to screw cut-out resistance by analyzing the mean torque/n-BMD (24). However, the study did not show statistical significance in max-torque/n-BMD between the groups with and without HA augmentation.

We concluded in this study that the measurement noise may cause statistical dispersion (22). However, this current study shows that max-torque/n-BMD was significantly higher in the presence of HA tubes. This is the first study to use Python, LOWESS, and the *scipy.signal.find_peaks* function. The sampling rate obtained from the torque gauge was 2,000 Hz, therefore, the total number of data series ranged from 50,000 to 100,000 plots with noise for each trial. The methods of data smoothing and peak extraction were effectively used to grasp the trends of the data series. LOWESS is a locally weighted nonparametric regression analysis method. Thus, the data curves calculated by LOWESS can be accurately fitted to the data, such as the manually measured torque. This is the first biomechanical study to show the effectiveness of LOWESS for analyzing nonparametric data.

Regarding radiologic parameters, we used intramedullary nails with neck-shaft angle of 125° for all cases. We tried to calculate the neck shaft angle of the proximal femur. However, the differences in the external rotation on radiographs made the calculation difficult. Further examination should be performed by using CT scans to clarify the details of radiologic parameters. Instead of angle parameters, we measured the telescoping amount of lag screws and found that the amounts of lag screw telescoping were lower in the HA group than that in the N group. Thus, it seems likely that the HA augments may increase the fixation of lag screws in the treatment of trochanteric femoral fractures. As for TAD, the distribution of BMD is reportedly higher on the outer side of the femoral head than on the inner side (28). Another study showed a TAD >25 mm is a predictor of post-operative cut-out (26). In this study, there was no observed association between TAD and max-torque in cases with TAD ≤25 mm. This suggests that when the lag screw is inserted deeper than 25 mm, the lag screw insertion torque is sufficiently high enough to prevent postoperative cut-out. Based

on these results, it is likely that HA augmentation would be the optimal approach to improve screw pull-out strength and to reduce the risk of screw cut-out in the treatment of trochanteric femoral fracture (22,23,29).

In this study, no complications were reported during the follow-up period. By contrast, cement augmentation is reportedly related to thermal osteonecrosis and bone cement syndrome, resulting in postoperative lag screw cut-out (9,13-16). Therefore, we believe that HA augmentation may be safer than cement augmentation in the treatment of trochanteric femoral fractures. Yamada *et al* (30) reported that HA-coated titanium implants would induce bone regeneration around the implant after the surgery. There may be an additional benefit of this surgical treatment that new bone formation would be induced. In this study, we could not find new bone formation in the analysis of postoperative radiographs. Quantitative analysis such as Quantitative Computed Tomography and DEXA around the screw would be needed to evaluate this effect.

Several limitations should be considered when interpreting the results of this study. Namely, the lack of postoperative clinical evaluations and the small sample size, made statistical evaluation difficult. Further studies are needed to evaluate the exact effects of HA augmentation in the treatment of trochanteric femoral fractures.

In conclusion, the max-torque/n-BMD ratio is improved by HA augmentation in the treatment of trochanteric femoral fracture surgery. Moreover, HA augmentation could increase the bone-implant interface and decrease the risk of cut-out after surgery.

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Availability of data and materials

The datasets generated and/or analyzed during the current study are available on the figshare repository (URL: <https://doi.org/10.6084/m9.figshare.21308985>).

Authors' contributions

TU wrote the original draft, acquired, analyzed, and interpreted the data and acquired the funding. NT conceived and designed this study, and wrote the original draft. HI acquired, analyzed and interpreted the data. GK wrote the original draft, analyzed and interpreted the data, and acquired the funding. HS, YH and IS analyzed and interpreted the data. YU, YN and HM reviewed the original draft, analyzed and interpreted the data, and administrated the project and resources. TU and NT confirm the authenticity of all

the raw data. All authors have read and approved the final manuscript.

Ethics approval and consent to participate

This study was approved by the Research Ethics Committee of Kainan Hospital (approval no. 20230413-01). Written informed consent was obtained from all participants before surgery.

Patient consent for publication

Written informed consent for the publication of any data and/or accompanying images was obtained from all patients preoperatively.

Competing interests

The authors declare that they have no competing interests.

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