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ORIGINAL ARTICLE

Perioperative teriparatide for preventing proximal junctional kyphosis and failure in patients with osteoporosis after adult thoracolumbar spinal deformity surgery: a prospective randomized controlled trial

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Abstract

Summary We conducted a randomized controlled trial to assess the preventive effect of perioperative teriparatide on proximal junctional kyphosis and proximal junctional failure (PJF) in osteoporosis patients undergoing adult spinal deformity surgery. Teriparatide (experimental group) and denosumab (active control) were administered. The teriparatide group demonstrated significantly better PJF incidence and VAS for back pain, EQ-5D than the control group.

Purpose This randomized controlled trial is aimed at investigating and comparing the effects of perioperative teriparatide and denosumab as an active control for preventing proximal junctional kyphosis (PJK) and proximal junctional failure (PJF) in patients with osteoporosis after adult spinal deformity (ASD) surgery.

Methods A total of 64 patients with osteoporosis, who planned to undergo ASD surgery, were randomly assigned to the teriparatide and denosumab groups. Treatment with teriparatide or denosumab in both groups was conducted from 3 months preoperatively to 3 months postoperatively based on the standard regimen for each medication. The primary outcome was PJK and PJF incidence within 1 year after ASD surgery. The secondary outcomes were patient-reported outcomes (PROs), bone mineral density (BMD), and dual-energy X-ray absorptiometry (DEXA) *t*-score of the hip.

Results The teriparatide group showed a lower incidence of PJK than the denosumab group (17.2% vs. 33.3%), although this difference was not statistically significant ($p = 0.165$ in a modified intention-to-treat (mITT) analysis). Furthermore, the teriparatide group exhibited a significantly lower incidence of PJF than the denosumab group (3.4% vs. 22.2%; $p = 0.034$ in the mITT analysis). As for the secondary outcomes, no significant differences in BMD of the hip were observed between the two groups at the 1-year follow-up. The teriparatide group showed significantly improved postoperative VAS for back pain and EQ-5D score.

Conclusions Perioperative teriparatide treatment of patients with osteoporosis after ASD surgery effectively reduced PJF incidence and postoperative back pain.

Keywords Adult spinal deformity · Osteoporosis · PJF · PJK · Teriparatide

Introduction

Proximal junctional kyphosis (PJK) and proximal junctional failure (PJF) are considered major complications that may lead to adult spinal deformity (ASD) surgery failure. Therefore, they are important issues in the field of spinal deformity. The reported incidence of PJK varies in the literature, ranging from 17 to 39%, and PJK frequently occurs within the first 2–3 months after surgery [1–8]. Despite the high PJK incidence, a definitive solution is yet to be established.

One-third of patients undergoing ASD surgery reportedly have osteoporosis; of these patients, two-thirds remain untreated for osteoporosis [9]. Considering that osteoporosis

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is a major risk factor for PJK, active interventions for osteoporosis in patients undergoing ASD surgery are important [10, 11]. Teriparatide, a synthetic form of the human parathyroid hormone (PTH 1–34), is frequently used as an anabolic agent for treating osteoporosis. Although the use of teriparatide in patients with osteoporosis undergoing ASD surgery helps prevent vertebral fractures and PJK, a high evidence level from research is currently lacking [12, 13].

The current prospective, randomized controlled trial utilized anabolic agent teriparatide and the anti-resorptive agent denosumab as an active control. The study aimed (i) to compare the incidence of PJK and PJF between two patient groups with osteoporosis, (ii) to ascertain whether teriparatide is more efficacious than denosumab in reducing PJK and PJF incidence, and (iii) to assess and compare patient-reported outcomes (PROs) between the two groups and changes in hip bone mineral density (BMD) between the two groups.

Materials and methods

Study design

This prospective, randomized, single-center, single-blind, parallel-group superiority trial targeted patients with ASD and osteoporosis. This study was approved by the institutional review board of the hospital (B-1901/514–001), and written informed consent was obtained from all participants before enrollment. The trial protocol was published at ClinicalTrials.gov (NCT04241211). The trial was reported in accordance with the Consolidated Standards of Reporting Trials (CONSORT) guidelines. This study was designed to evaluate the effectiveness of teriparatide in preventing proximal junctional problems after ASD surgery in patients with postmenopausal osteoporosis. For the study group, teriparatide treatment was planned. Owing to ethical considerations, denosumab treatment was planned as the active control.

Participants

Postmenopausal women with ASD and osteoporosis were recruited from a single spinal center at a tertiary care teaching institution. The inclusion criteria were as follows: age of 50–85 years, postmenopausal women with osteoporosis (average dual-energy X-ray absorptiometry (DEXA) T-score of L1–4 and the lowest T-score among the femoral neck and femoral total less than − 2.5), individuals planning for deformity correction due to symptomatic degenerative thoracolumbar spinal deformities (e.g., lumbar kyphosis and thoracolumbar scoliosis), and individuals who fully understood the contents of the clinical trial and signed the consent form. The exclusion criteria were as follows: individuals already receiving treatment for osteoporosis; presence of other spinal diseases impairing walking, such as thoracic and/or cervical myelopathy; peripheral vascular disease; any syndromic or neuromuscular disease; serious uncontrolled medical comorbidities, such as sepsis or malignancy, which could cause disability or exacerbate the overall medical condition; patients suffering from other uncontrolled chronic conditions that could affect the study results (endocrine, metabolic, kidney disease, rheumatoid arthritis.); and psychiatric disorders (dementia, intellectual disability, severe drug addiction, etc.) or alcohol addiction.

Randomization, blinding, and follow-ups

All participants were randomly assigned to either the teriparatide or denosumab group at a 1:1 ratio. Prior to enrollment, the patients were assigned to each group by a research assistant who was not involved in the study using a random number table generated from http://www.randomization.com. The allocation was concealed and presented to the investigators with the first prescription of the medication. Considering the nature of the study, both the investigators and participants were aware of the prescribed medication. Therefore, only assessors and data analysts were blinded.

All participants completed questionnaires regarding their demographic characteristics, medical history, and PRO instruments. Additionally, all participants underwent hip BMD and DEXA t-score assessments prior to study initiation. Radiographic evaluation was conducted preoperatively to assess the spinopelvic parameters. Deformity in participants was classified based on the Scoliosis Research Society (SRS)–Schwab system as follows: (i) isolated coronal deformity (type T, L, or D and SVA < 4 cm), (ii) isolated sagittal deformity (type N and SVA > 4 cm), and (iii) mixed coronal and sagittal deformity (type T, L, or D and SVA > 4 cm) [14, 15].

The occurrence of PJK and PJF, as well as PRO measures, was evaluated at 3 months, 6 months, and 1 year postoperatively. Postoperative spinopelvic parameters were radiographically evaluated within 2 weeks postoperatively. Hip BMD was assessed preoperatively and at 1 year postoperatively. Adverse events were reported and documented continuously irrespective of their causal relationship with the investigational drugs. The details of adverse events including the date of occurrence, type, and severity, as well as the investigators' opinion on the potential relationship between the study drug and consequent dropouts, were recorded.

All radiographic evaluations including PJK and PJF assessments were conducted using biplanar stereo-radiographic full-body imaging (EOS, Paris, France). Additionally, to assess complications, such as screw loosening and endplate fractures, which are considered difficult to detect on EOS, routine computed tomography evaluations

were performed at 1 year postoperatively. PJK, PJF, and spinopelvic parameters were radiologically evaluated by an independent spine surgeon, blinded to the group assignments (co-author: Ohsang Kwon). Additionally, PRO surveys were administered by a research assistant blinded to the group assignments. Data were analyzed by an independent spine surgeon, who was also unaware of the group assignments (co-author: Ohsang Kwon).

Interventions

The groups were treated with teriparatide or denosumab from 3 months preoperatively to 3 months postoperatively based on the standard regimen for each medication. This treatment duration was based on a previous study, in which teriparatide was commonly administered within 2–3 months postoperatively [16]. For teriparatide treatment, the Forsteo® injection (Lily & Co.) was used, and the participants were subcutaneously injected with a standard dose of 20 mcg daily from 3 months preoperatively to 3 months postoperatively. For denosumab treatment, Prolia® (Amgen Inc.) was used, and the participants were subcutaneously injected with a standard dose of 60 mg every 6 months (one injection at 3 months preoperatively and another injection at 3 months postoperatively). In the denosumab group, the participants were instructed to orally take 1000 mg of calcium and at least 400 IU of vitamin D daily. Following treatment completion with each medication, both groups received bisphosphonate until the final follow-up (Fig. 1).

Surgical procedures

A single surgeon performed ASD surgery in all participants; no significant differences in surgical techniques were observed among the patients. All surgeries were conducted with the patients in the prone position on a Mizuho OSI modular table system (Mizuho OSI, Union City, CA, USA). Patients were positioned in prone, lateral radiographs were utilized to calculate the pelvic incidence (PI)–lumbar lordosis (LL) mismatch, and the angle required for correction was determined. The surgical method including the fusion length and type of osteotomy was determined based on the calculated PI–LL mismatch. We selected biomechanically stable T10 as the upper instrumented vertebra (UIV), as it benefits from the presence of true ribs. Iliac screw insertion has become a common practice to address the high risk of failure and nonunion at the L5–S1 level. Dual rods made of a 6.0-mm-diameter titanium or 5.5-mm cobalt-chrome alloy were routinely used to prevent rod fractures and ensure stable fixation. All pedicle screws were polyaxial, with diameters of 5.0–7.5 mm, and were tailored to the patients' pedicle size. Cement augmentation or ligament augmentation was not performed in any case.

Measurements and outcomes

Primary outcome

The primary outcome was PJK or PJF incidence within 1 year after ASD surgery. PJK and PJF were defined based on previous studies. PJK was defined as a proximal junctional sagittal Cobb angle of ≥ 10° between the lower endplate of

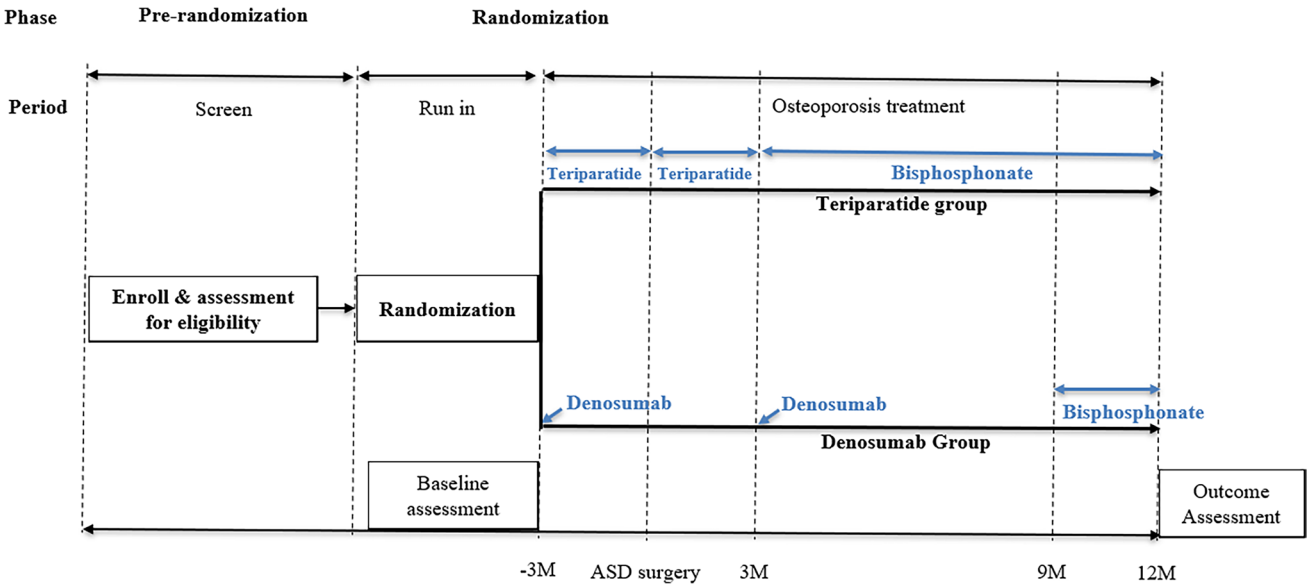

Fig. 1 Study design

the UIV and the upper endplate of two vertebrae above the UIV (UIV + 2), with an increase of ≥ 10° compared to the preoperative angle. PJF was defined as the need for revision surgery for a vertebral fracture at the UIV or UIV + 1, subluxation between the UIV and UIV + 1, fixation failure, or development of a neurological deficit [17].

Secondary outcomes

The secondary outcomes were changes of PROs and hip BMD. Hip BMD was measured as an absolute value according to the ISCD guidelines. The PROs included the Visual Analog Scale (VAS) score for back pain, Oswestry Disability Index (ODI), EuroQol-5 Dimensions (EQ-5D) score, and SRS-22r score. The VAS for back and leg pain comprises a 10-cm line, with "none" (0) on one end of the scale and "disabling pain" (10) on the other. The ODI comprises ten items and evaluates overall function related to back symptoms using a self-administered questionnaire, with the total score being evaluated on a scale of 0–100 [18]. The EQ-5D scale measures the health-related quality of life (HRQOL), with the score ranging from zero to one (perfect health) [19]. The SRS-22r is a scoliosis-specific HRQOL questionnaire that consists of 22 items and five domains. This scale is reliable and valid for populations with ASD [20–22].

Sample size estimation

The total target number of study participants was set at 64 individuals, with 32 participants allocated to each group. The target number of participants was calculated based on previous studies. Although the incidence varied across studies, the reported incidence of PJK after spinal deformity surgery was high at 39% [23]. Additionally, in a previous retrospective study, the PJK incidence in ASD surgery patients treated with teriparatide was reported to be 9.3% [13]. Therefore, assuming an alpha of 0.05, a desired power of 0.80, and a follow-up loss of 5%, a sample size of 32 participants per group was required.

Statistical analysis

Descriptive analysis was performed to summarize the participant characteristics. To test for homogeneity between groups regarding demographic characteristics and baseline data, we employed t-tests, chi-square test, and Fisher's exact test. Continuous variables were compared between groups using an independent t-test, with values presented as means ± standard deviations. Categorical variables were compared using the chi-square test and Fisher's exact test.

All analyses were conducted on a modified intention-to-treat (mITT) basis. The mITT population comprised all participants who were randomly assigned to receive osteoporosis treatment and had available data after ASD surgery. For missing values, imputation was performed using the "last observation carried forward" or "last observation carried backward" method. Additionally, a per-protocol analysis was conducted on the primary outcome data of participants who completed follow-up until 12 months without any major deviations from the protocol.

For the primary outcome, PJK and PJF incidence up to 1 year postoperatively was compared between the two groups using the chi-squared test. For the secondary outcomes, the hip BMD, hip DEXA t-score, and PROs at 1 year postoperatively were compared between the two groups using Student's t-test. All statistical analyses were performed using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). All tests were two-sided, with statistical significance set at $p < 0.05$.

Results

Participants

From January 2020 to November 2022, a total of 207 individuals who were scheduled for ASD surgery were screened for eligibility; among them, three declined to participate in the trial, whereas 140 did not meet the inclusion criteria. The remaining 64 participants were randomly assigned to either the teriparatide group ($n = 32$) or denosumab group ($n = 32$). Eight participants were excluded from the mITT analysis because they canceled their surgery. Two participants were excluded from the per-protocol analysis because of major protocol deviations caused by adverse events (Fig. 2).

No significant differences in baseline clinical and preoperative composite alignments as well as in pre- and postoperative spinopelvic parameters were observed between the two groups ($p > 0.05$ for all) (Tables 1 and 2).

Primary outcomes (PJK and PJF incidence)

The mITT analysis showed no significant difference in PJK incidence at 1 year after ASD surgery between the two groups (teriparatide, 17.2% vs. denosumab, 33.3%, $p = 0.165$). The PJF incidence at 1 year after ASD surgery was significantly lower in the teriparatide group than in the denosumab group (teriparatide, 3.4% vs. denosumab, 22.2%, $p = 0.034$). The per-protocol analysis also revealed no significant difference in PJK incidence at 1 year after ASD surgery between the two groups (teriparatide, 18.5% vs. denosumab: 33.3%, $p = 0.214$). The PJF incidence at 1 year after ASD surgery was significantly lower in the teriparatide group than in the denosumab group (teriparatide, 3.7% vs. denosumab: 22.2%, $p = 0.043$) (Fig. 3).

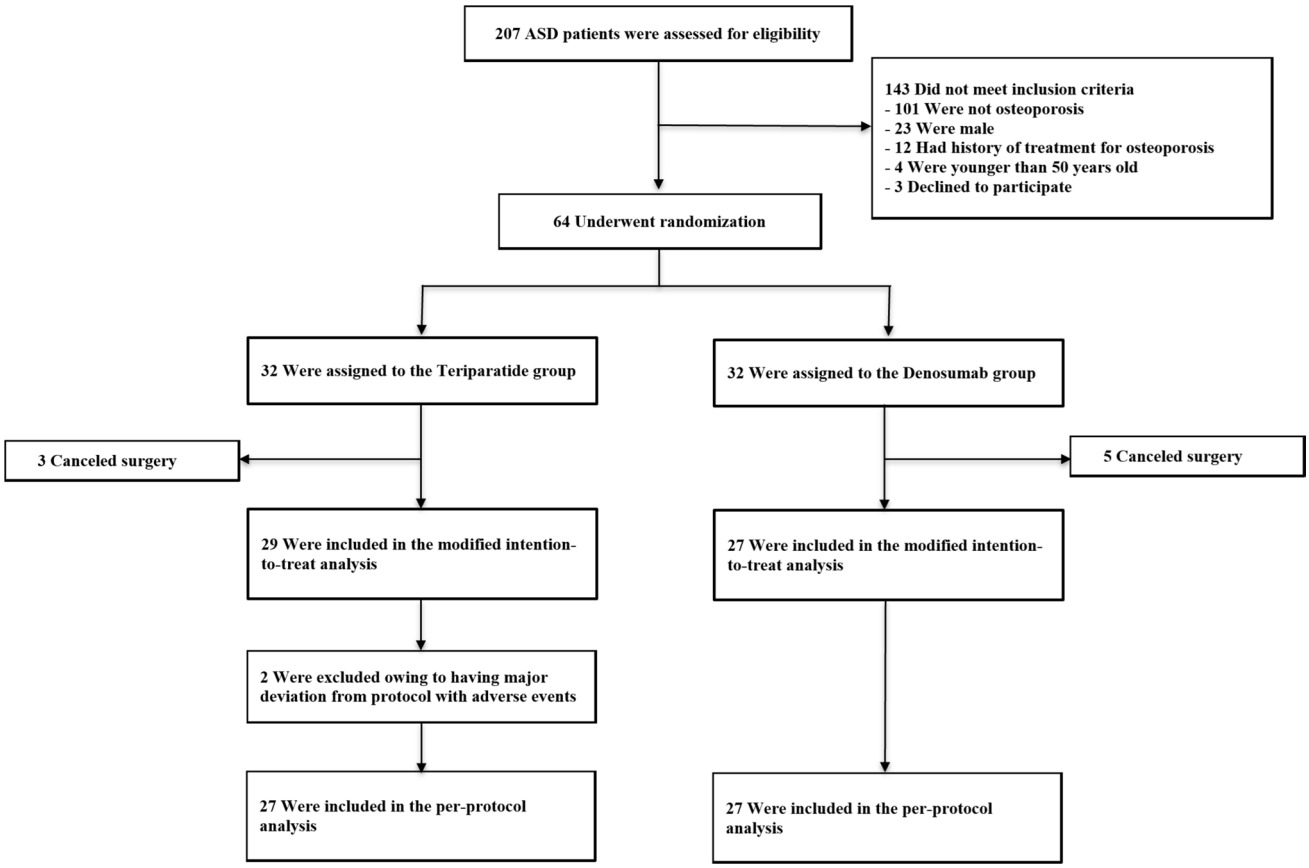

Fig. 2 Flow diagram of participant enrollment

Secondary outcomes (hip BMD and PROs)

The change of hip BMD at 1 year after ASD surgery did not significantly differ between the two groups ($p = 0.496$). One year after ASD surgery, the teriparatide group showed significantly better results than the denosumab group in terms of change from baseline in VAS for back pain and EQ-5D in PROs (VAS for back pain: $p = 0.008$, EQ-5D: $p = 0.026$). However, no significant differences in ODI and SRS-22 scores were observed between the two groups (Fig. 4 and Table 3).

Adverse events

No major life-threatening adverse events occurred throughout the trial. Regarding adverse events related to drug treatment, one participant in the teriparatide group experienced vomiting, while another had diarrhea. No adverse events were detected in the denosumab group (Table 4). In terms of surgery-related complications, a small number of cases of surgical site infection, screw pull-out, and neurological deterioration were observed (Table 5).

Discussion

Compared to denosumab, teriparatide did not reduce the PJK incidence; however, teriparatide significantly reduced the PJF incidence at 12 months after ASD surgery in menopausal women with osteoporosis and was significantly effective in terms of pain-related PROs at 12 months after ASD surgery.

The use of teriparatide in this trial significantly reduced PJF, a finding supported by various studies on the application of teriparatide in prior lumbar spine fusion surgery. The use of teriparatide in patients with osteoporosis after fusion surgery decreases the risk of vertebral fractures, improves the fusion rate, and lowers the possibility of fixation failures including screw loosening [13, 24–28]. The mechanism by which teriparatide reduces the risk of vertebral fractures and screw loosening while also improving the fusion rate in standard lumbar fusion surgery may be similarly effective in addressing proximal junctional issues in adult ASD surgery. Proximal junctional complications frequently result from fractures in the UIV or its neighboring vertebrae, as well as issues such as screw loosening at the UIV. In addition, a reduction in the fusion rate at the proximal end can

Table 1 Baseline characteristics of patient cohort

	Teriparatide group ($N=29$)	Denosumab group ($N=27$)	p-value
Age (years)	70.9 ± 12.8	71.7 ± 7.4	0.786
CCI	0.86 ± 1.06	0.78 ± 0.90	0.750
BMI (kg/m^2)	25.1 ± 4.7	25.9 ± 4.4	0.524
Hip BMD (g/cm^2)	0.651 ± 0.462	0.569 ± 0.080	0.368
DEXA (t-score)	− 3.0 ± 0.4	− 2.9 ± 0.4	0.190
Composite alignment, *n* (%)			
Isolated coronal deformity (Type T, L, or D + SVA < 4 cm)	3 (10.3%)	2 (7.4%)	0.700
Isolated sagittal deformity (Type N + SVA > 4 cm)	16 (55.2%)	19 (70.4%)	0.240
Mixed coronal and sagittal deformity (Type T, L, or D + SVA > 4 cm)	10 (34.5%)	6 (22.2%)	0.310
PROs			
VAS for back pain	7.7 ± 2.6	7.5 ± 2.3	0.794
ODI	24.3 ± 9.7	24.1 ± 7.4	0.933
EQ-5D	0.20 ± 0.28	0.29 ± 0.24	0.194
SRS-22r score			
Function	2.49 ± 0.94	2.28 ± 0.52	0.312
Pain	2.83 ± 2.64	2.24 ± 0.72	0.271
Self-image	2.12 ± 0.77	1.80 ± 0.52	0.078
Mental health	2.68 ± 0.91	2.56 ± 0.64	0.622
Total	2.45 ± 0.65	2.28 ± 0.49	0.294

Bold values indicate statistical significance. Values are represented as mean ± SD and *n* (%). Abbreviations: *CCI*, Charlson Comorbidity Index; *BMI* body mass index, *BMD* bone mineral density, *DEXA* dual-energy X-ray absorptiometry, *SVA* sagittal vertical axis, *VAS* Visual Analog Scale, *ODI* Oswestry Disability Index, *EQ-5D* European Quality of Life-5 dimensions, *SRS-22r* Scoliosis Research Society-22 revised

Table 2 Pre-operative and post-operative spinopelvic parameter

	Teriparatide group ($N=29$)	Denosumab group ($N=27$)	p-value
Pre-operative			
PT (°)	30.6 ± 13.6	34.5 ± 10.5	0.229
PI (°)	45.5 ± 11.2	49.8 ± 12.2	0.175
LL (°)	− 8.5 ± 17.3	− 3.4 ± 22.1	0.338
PI–LL (°)	54.0 ± 20.7	53.1 ± 27.4	0.880
TK (°)	12.4 ± 14.2	14.3 ± 14.4	0.638
SVA (mm)	156.3 ± 77.8	157.6 ± 73.1	0.952
Post-operative			
PT (°)	22.3 ± 12.4	23.4 ± 8.0	0.708
PI (°)	46.9 ± 9.8	50.2 ± 11.6	0.252
LL (°)	37.4 ± 8.8	38.4 ± 7.6	0.634
PI–LL (°)	9.5 ± 10.5	11.8 ± 10.9	0.433
TK (°)	12.4 ± 14.2	14.3 ± 14.4	0.931
SVA (mm)	45.4 ± 36.5	46.5 ± 41.3	0.918

Bold value indicates statistical significance. Values are represented as mean ± SD. Abbreviations: *PT* pelvic tilt, *PI* pelvic incidence, *LL* lumbar lordosis, *SVA* sagittal vertical axis, *TK* thoracic kyphosis

exacerbate proximal junctional problems. In the current trial, although no significant difference in PJK incidence was identified between the two groups, PJF was reduced in the teriparatide group compared to that in the control group. Thus, even if PJK occurs, the use of teriparatide may prevent further collapse and inhibit metal failure, thereby preventing the progression to PJF.

In this trial, the hip BMD and hip DEXA t-score at 1 year after treatment did not significantly differ between the teriparatide and denosumab groups. The reasons for this finding are as follows. First, after ASD surgery, the spine is instrumented, making it impossible to measure the spine BMD and spine DEXA t-score. Therefore, BMD and DEXA score measurements were obtained through the hip, making it difficult to accurately determine changes in the spine BMD and spine DEXA score. Second, teriparatide was used for only 3 months preoperatively and 3 months postoperatively in this trial based on evidence that anabolic effect is maximized within 6 months after administration of teriparatide, so-called "anabolic window" [29]; subsequently, we switched to bisphosphonate. Owing to the short duration of teriparatide use, no significant difference in the BMD and DEXA t-score was observed in the teriparatide group compared to that in the denosumab group.

Interestingly, the teriparatide group showed a significant improvement in VAS for back and EQ-5D. Several previous studies have reported that teriparatide reduces back pain. Moreover, it not only promotes healing and alleviates back pain in patients with fractures but also significantly reduces back pain in patients without fractures. The

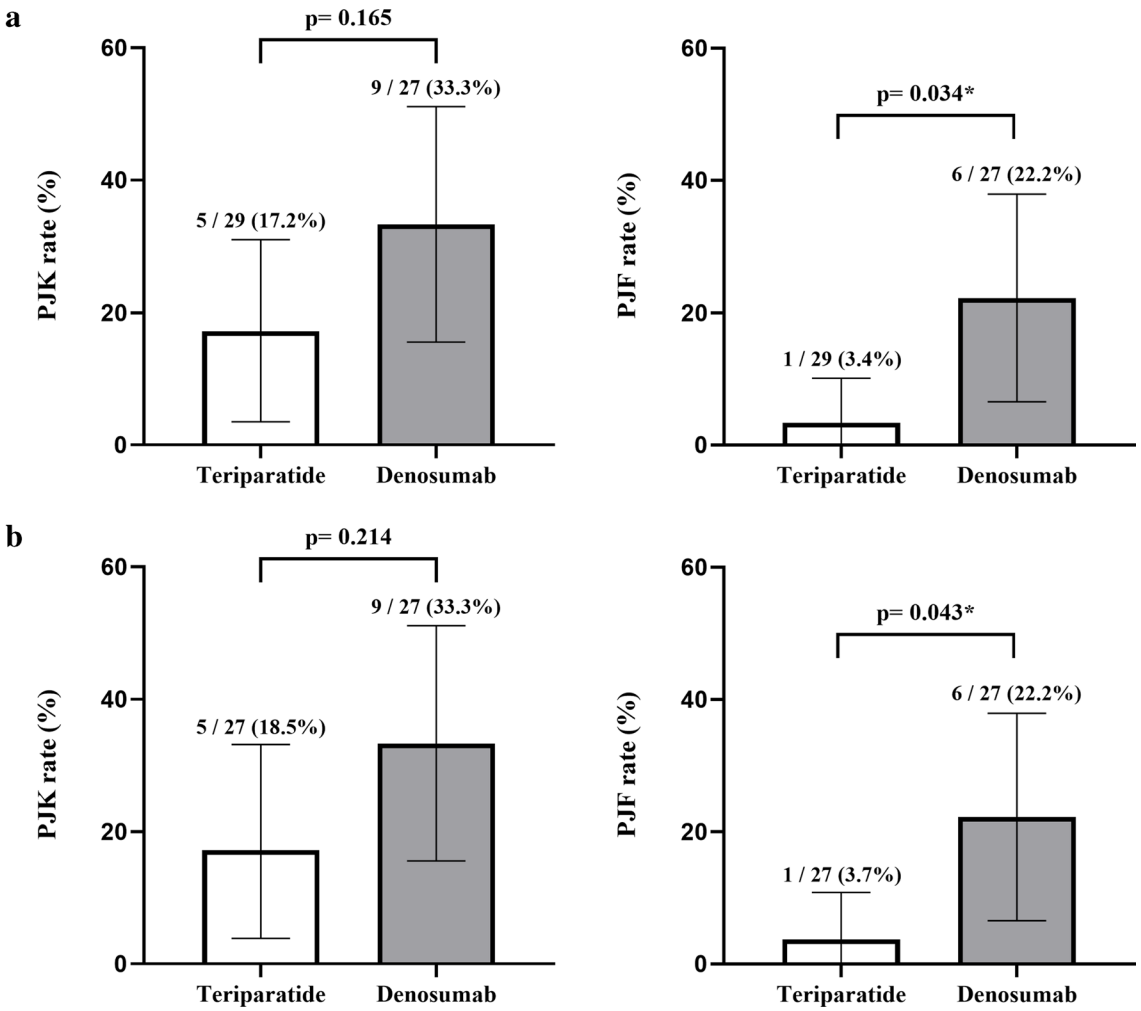

Fig. 3 Incidence of proximal junctional kyphosis (PJK) and proximal junctional failure (PJF) up to 12 months postoperatively (primary outcomes). Data are presented using both **a** modified intention-to-treat (mITT) and **b** per protocol. Error bars denote the 95% confidence intervals. * indicates statistical significance

proposed mechanisms for back pain reduction include teriparatide's role in preventing new fractures, its interaction with parathyroid hormone receptors in the CNS to modulate pain perception, and the hypothesis that teriparatide helps resolve micro-damage. However, the exact mechanisms remain unclear. Therefore, basic research to elucidate these mechanisms is considered necessary [30–34].

This study has several limitations. First, unexpectedly, some surgeries were canceled, leading to a higher-than-anticipated dropout rate. After the final participant in the initially planned sample completed their follow-up, we analyzed the collected data. While no significant differences were observed between the two groups in terms of PJK, we identified a significant difference in the incidence of PJF. This finding aligns with previous retrospective studies indicating that teriparatide primarily influences PJF [13]. Based on this, we decided not to pursue additional participant recruitment. Second, as this trial focused on postmenopausal women with osteoporosis, generalizing the results to the general population is challenging. In particular, teriparatide use in elderly patients with ASD and osteopenia should be investigated in future studies. Third, although implementing a full treatment protocol for 1 year would likely yield the greatest benefits of teriparatide, the teriparatide (Forteo®) injection we used requires daily administration. We believe that maintaining treatment for a full year would be challenging due to the low compliance observed among patients. Therefore, a reasonable compromise for the protocol needs to be established. Considering that most cases of PJK occur within 3 months postoperatively and that the anabolic window of teriparatide reaches its peak at around 6 months, we administered teriparatide treatment for a total of 6 months—starting 3 months preoperatively and continuing for 3 months postoperatively.

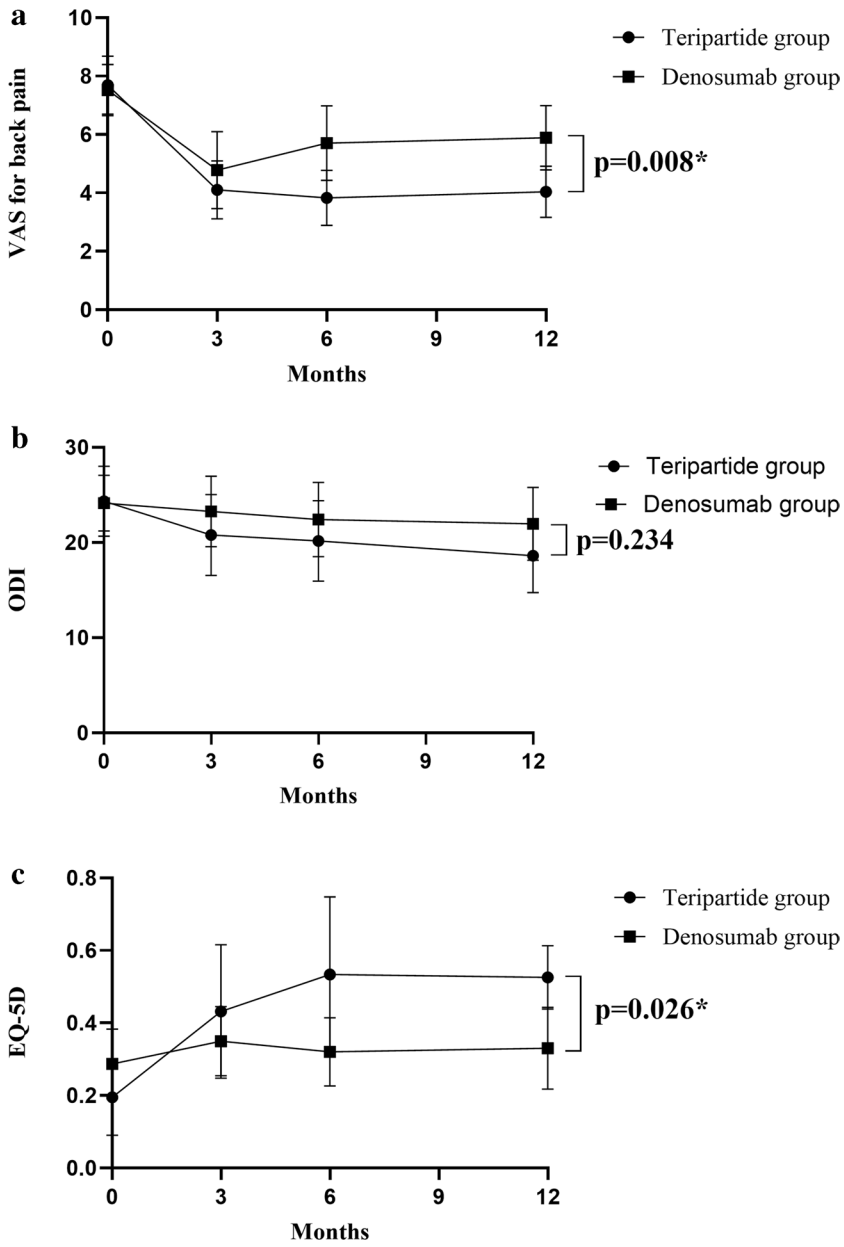

Fig. 4 Patients-reported outcomes (PROs) at the follow-up assessments (baseline, 3 months, 6 months, and 12 months). Error bars denote the 95% confidence intervals. **a** Visual Analog Scale (VAS); **b** Oswestry Disability Index (ODI); **c** European Quality of Life-5 dimensions (EQ-5D). * indicates statistical significance

Third, in this study, denosumab and teriparatide were administered for 6 months and then discontinued. Since this treatment duration is shorter than standard protocols, caution is necessary. Although a 6-month treatment period was planned for both groups, considering patient compliance and the anabolic window of teriparatide, discontinuation after 6 months may lead to potential problems such as fractures and worsening osteoporosis. In particular, the anti-resorptive effect of denosumab is known to be reversible, and upon discontinuation, bone turnover markers have been reported to increase beyond pre-treatment levels, while bone mineral density declines rapidly. Furthermore, the risk of fractures after discontinuing denosumab has been reported to be similar to that of untreated patients [35]. To mitigate the rebound phenomenon that may occur after discontinuing denosumab and to address ethical concerns, bisphosphonates were administered as a consecutive treatment. Several previous studies have shown that using bisphosphonates as a consecutive treatment after discontinuing denosumab can effectively reduce the rebound phenomenon and subsequently lower the risk of fractures [36–39]. Similarly, in our study, although hip BMD decreased in the denosumab group compared to baseline, there was no significant difference when compared to the teriparatide group (Table 3). Additionally, no fractures occurred in either group. Likewise, in the teriparatide group, bisphosphonates were used as a consecutive treatment to minimize potential problems that could arise upon discontinuation of teriparatide.

Table 3 Bone mineral density (BMD) and patient-reported outcomes (PROs) one year after surgery

	Teriparatide group ($N=29$)	Change from baseline	Denosumab group ($N=27$)	Change from baseline	p-value
Hip BMD (g/cm^2)	0.742 ± 0.912	0.090 ± 0.885	0.543 ± 0.044	− 0.027 ± 0.723	0.496
PROs					
VAS for back pain	4.0 ± 2.3	− 3.7 ± 2.5	5.9 ± 2.8	− 1.6 ± 3.1	**0.008***
ODI	18.6 ± 10.2	− 5.7 ± 11.4	22.0 ± 9.7	− 2.2 ± 10.6	0.234
EQ-5D	0.53 ± 0.54	0.33 ± 0.59	0.33 ± 0.28	0.04 ± 0.28	**0.026***
SRS-22 score					
Function	2.83 ± 0.77	0.34 ± 0.82	2.55 ± 0.93	0.36 ± 1.29	0.950
Pain	3.72 ± 1.60	0.89 ± 1.39	2.77 ± 0.87	0.62 ± 1.24	0.452
Self-image	2.67 ± 0.97	0.55 ± 0.94	2.72 ± 0.94	0.99 ± 1.23	0.133
Mental health	3.15 ± 0.88	0.48 ± 0.91	3.14 ± 1.17	0.67 ± 1.36	0.521
Satisfaction	3.54 ± 1.00	-	3.53 ± 0.92	-	-
Total	3.11 ± 0.66	0.66 ± 0.70	2.87 ± 0.80	0.67 ± 1.15	0.971

Bold value indicates statistical significance. Values are represented as mean ± SD. Abbreviations: *BMD* bone mineral density, DEXA dual-energy X-ray absorptiometry, *SVA* sagittal vertical axis, *VAS* Visual Analog Scale, *ODI* Oswestry Disability Index, *EQ-5D* European Quality of Life-5 dimensions, *SRS-22r* Scoliosis Research Society-22 revised

Table 4 Summary of adverse events related to drug treatment

Adverse event	Teriparatide group ($N=29$)		Denosumab group ($N=27$)	
	N	(%)	N	(%)
Vomiting	1	4.17	0	0
Diarrhea	1	4.17	0	0
Total number	2	8.33	0	0

Values are represented as n (%)

Table 5 Summary of surgery-related complications

Surgery-related complications	Teriparatide group ($N=29$)		Denosumab group ($N=27$)	
	N	(%)	N	(%)
Surgical site infection	0	0	1	3.7
Screw pull-out	1	3.4	1	3.7
Neurological deterioration	2	6.9	3	11.1
Total number	3	10.3	5	18.5

Values are represented as n (%)

Lastly, although most proximal junctional problems occur within 2–3 months postoperatively, progressive failure including pseudarthrosis, hardware fracture or screw loosening, or progressive osteoporotic compression due to fracture often becomes apparent in the second or even third year after surgical treatment. Therefore, long-term follow-up will be necessary to obtain more definitive results.

Conclusion

Perioperative teriparatide treatment in ASD surgery for patients with osteoporosis reduced PJF incidence and effectively reduced postoperative back pain.

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Data availability All data are available with the corresponding author on reasonable request.

Declarations

Competing interest Jin-Ho Park, Ohsang Kwon, Jae Heouk Choi, Jin S. Yeom, Sang-Min Park, Cheol Hyun Kim, and Ho-Joong Kim declare that they have no conflict of interest.

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