Article

Effect of Stepped Rehabilitation Training on Hip Joint Function and Bone Metabolism Markers in Patients Undergoing Hip Arthroplasty

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AIM: This study investigates the effects of stepped rehabilitation training on hip joint function and bone metabolism markers in patients undergoing hip arthroplasty (HA).
METHODS: This retrospective analysis included 97 patients who underwent HA in our hospital between December 2021 and December 2023. The patients were divided into a control group (52 cases) and an observation group (45 cases) based on different rehabilitation training approaches. The control group received routine nursing and rehabilitation exercises, while the observation group underwent stepped rehabilitation training in addition to the standard care. The surgery-related indicators, hip joint function, bone metabolism-related markers, and quality of life at 1, 2, and 4 weeks of training were compared between the two groups. Repeated-measures analysis of variance (ANOVA) was applied to explore the changes in hip function indexes and bone metabolism-related markers at different time points, and their interactions with the groups were examined. The association between changes in bone metabolism-related markers from baseline to week 4 and corresponding changes in Harris hip scores over the same period was assessed using locally weighted regression scatterplot smoothing (LOWESS) method.
RESULTS: The hip joint range of motion, hip abduction strength arm, Harris hip score, levels of serum bone alkaline phosphatase (BALP), type I collagen amino-terminal lengthening peptide (PINP) and osteocalcin, Barthel index score, and 36-Item Short Form Health Survey (SF-36) scores sequentially increased in both groups at weeks 1, 2, and 4 of the training, with the observation group exhibiting higher values than the control group ($p < 0.05$). Levels of type I collagen carboxy-terminal peptide (CTX), intact parathyroid hormone (iPTH), and tartrate-resistant acid phosphatase 5b (TRACP-5b) decreased sequentially in both groups at weeks 1, 2, and 4 of the training, with the observation group demonstrating lower levels than the control group ($p < 0.05$). Furthermore, significant differences were observed in the time, inter-group, and interaction effects of hip joint function and bone metabolization-related markers between the two groups during the training period ($p < 0.05$). Moreover, a nonlinear association was found between the changes in bone metabolism-related markers from baseline to week 4 and the corresponding changes in Harris hip scores over the same time points. Additionally, there was no statistically significant difference in the total postoperative complication rate between the observation group (6.67%) and the control group (15.38%) ($p = 0.177$).
CONCLUSIONS: Stepped rehabilitation training can promote hip joint function recovery in patients undergoing hip arthroplasty, improve bone metabolic balance through upregulating osteogenic markers and suppressing osteoclastic activity, and ultimately enhance quality of life.

Keywords: stepped rehabilitation training; hip arthroplasty; hip function; markers of bone metabolism

Introduction

Hip arthroplasty (HA) is a crucial surgical intervention used to manage hip joint disorders, femoral head necrosis, and femoral neck fractures, which has been found to be highly effective in alleviating pain, correcting hip deformities, and restoring hip function [1,2]. However, approximately 22% to 75% of patients fail to regain full hip function within six months post-operation, a condition prevalent among elderly patients with limited mobility and poor compliance

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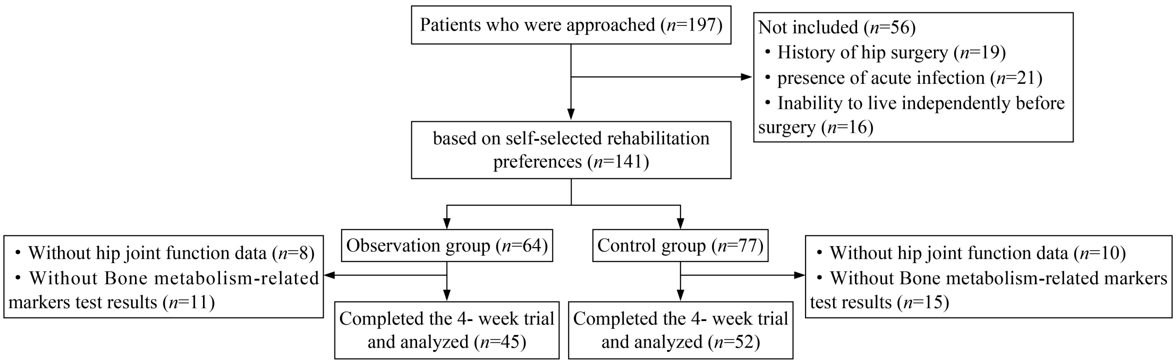

Fig. 1. Flow diagram of patient selection and treatment.

with rehabilitation approaches. This variability primarily stems from age-related sarcopenia, which impairs muscle regeneration, persistent maladaptive movement patterns after surgery, and suboptimal adherence to rehabilitation due to psychosocial barriers. Such individuals require long-term rehabilitative training. Inadequate or delayed rehabilitation can lead to hip dislocation, joint stiffness, and muscle atrophy [3–6].

Conventional nursing strategies predominantly emphasize reducing surgical risks; however, they often fail to provide personalized care and effective rehabilitation [7]. A study by Zhao *et al*. [8] reported that patients who received conventional nursing care after hip arthroplasty experienced prolonged postoperative pain, delayed knee joint functional recovery, and increased agitation compared to those receiving painless rehabilitation nursing care. Similarly, Wang and Lin [9] demonstrated that conventional nursing approaches were less efficient, resulted in slower recovery progress, and were associated with higher complication rates compared to rehabilitation strategies guided by machine learning following total hip arthroplasty.

Thus, developing advanced rehabilitation strategies to optimize postoperative recovery has emerged as a research priority. Stepped rehabilitation training, a novel rehabilitation model involves phasing and progressively intensifying training based on patient responsiveness and individualized situations. This strategy aims to promote rapid recovery of joint function and enhance daily living capabilities [10]. The stepped rehabilitation model focuses on both immediate rehabilitation outcomes and long-term functional recovery, ultimately improving quality of life. A study by Moore *et al*. [11] demonstrated considerable improvements in average daily step counts, Berg balance scale scores, and 6-minute walk distance among stroke patients receiving stepped rehabilitation compared to those undergoing conventional care. Furthermore, significant improvement in self-selected and maximum gait speeds was observed, indicating a substantial improvement in walking and balance functions. Chen *et al*. [12] reported that a high-intensity stepped conditioning program effectively alleviated knee pain and improved sport-specific agility performance and cardiopulmonary fitness in a male badminton player with left knee patellar tendinosis and calcification. The findings of Wen *et al*. [13] revealed that a 10-week step aerobics program significantly reduced bone resorption and enhanced functional fitness among postmenopausal women with low bone mass, demonstrating positive impacts on bone health and overall physical condition. Spencer-Gardner *et al*. [14] found that stepped rehabilitation training following hip arthroscopy surgery effectively improved hip joint functionality and daily activities.

Nevertheless, systematic investigations evaluating the effects of stepped rehabilitation training on hip joint function and bone metabolism biomarkers in patients undergoing HA remain limited. Therefore, this study intends to systematically explore the effects of stepped rehabilitation training on hip function and bone metabolism markers in patients undergoing HA, assessing the advantages of this strategy in promoting hip function recovery and regulating bone metabolism. The findings of this study will provide valuable insights for the clinical development of scientifically informed and reasonable rehabilitation training programs.

Methods

Research Participants

This retrospective study enrolled 97 patients who underwent total HA at Shanghai Baoshan District Wusong Central Hospital between December 2021 and December 2023. Based on self-selected rehabilitation preferences and various rehabilitation training methods, the patients were divided into observation (45 cases) and control (52 cases) groups (Fig. 1). The control group received routine nursing and rehabilitation training after surgery, while the observation group received stepped rehabilitation training in addition to routine nursing.

The study was conducted following the principles of the Declaration of Helsinki and obtained approval from the Ethics Committee of Shanghai Baoshan District Wusong Central Hospital (Approval No. 2023-4). Informed consent was obtained from all patients or their families before participation.

Inclusion Criteria and Exclusion Criteria

The inclusion criteria for patient recruitment were as follows: (1) patients with radiologically confirmed hip pathology diagnosed via X-ray, computed tomography (CT), or other imaging approaches; (2) patients with clear indication for HA; (3) those with normal preoperative muscle strength in the lower extremities; (4) those with American Society of Anesthesiologists (ASA) physical status classification grade II-IV; (5) patients undergoing unilateral primary HA without prior surgical intervention in the hip; and (6) individuals with complete clinical data.

Exclusion criteria included (1) history of hip surgery; (2) diagnosed cognitive impairment or psychiatric disorders; (3) presence of acute infection; (4) concomitant fractures at other sites or diseases affecting weight-bearing joints; (5) severe major organ dysfunction; (6) bone tumor; (7) coagulation dysfunction; (8) neuropathy or suppurative lesions in the hip or adjacent muscles; (9) inability to live independently before surgery.

Postoperative Rehabilitation Training Protocols

The control group received conventional postoperative nursing and rehabilitation training. One day before surgery, patients received video or verbal instruction to perform pre-functional exercises, including hip lifts, ankle rotations, ankle pumps, and quadriceps contraction training. Postoperatively, the patients participated in daily 30-minute sessions that continued until hospital discharge, covering proper positioning, dislocation-prevention education, joint mobility training, lower-limb muscle strengthening, and ambulation training.

The observation group underwent stepped rehabilitation training in addition to the standard care received by the control group. During this four-stage rehabilitation program, family members were required to accompany and actively participate with the patient:

(1) The first stage is basic training, mainly focusing on in-bed exercises to reactivate neuromuscular function and help prevent complications such as deep vein thrombosis. Under the guidance of a rehabilitation therapist at the bedside, patients performed exercises twice a day for 30 minutes each session. These activities included sitting up in bed, repositioning in bed, ankle rotation, ankle pump exercises, elevating the affected limb, joint flexion, and muscle contraction. Once the patients were able to perform these exercises independently and attained a muscle strength of grade 3 or greater in the affected lower limb, they passed the assessment and advanced to the next stage of training.

(2) After passing the first-stage assessment, the patients were advanced to stage two: single-task training. This training stage focused on specific activities of daily living and joint functions through individual exercises. Under therapist guidance, patients were engaged in two 30-minute sessions daily, exercising various tasks, including brushing teeth, washing the face, dressing, sitting, standing, walking on the ground, repositioning in bed, bed-to-chair transfers, picking up objects, and going up and down stairs. Once the patients practiced these tasks independently, they were considered to have met the criteria and proceeded to the next stage of training.

(3) Upon meeting all single-task criteria, patients were advanced to stage three. The third stage emphasized practicing sequences of daily-life activities in one continuous flow. They performed the series of actions twice independently before discharge to qualify the sage requirements, including entering through the door, going up and down stairs, changing shoes, picking up objects, getting into and out of bed, changing clothes, sitting down and standing up for meals, using the toilet, washing the face, reading at a desk, and changing shoes to leave. Once the patients performed these tasks twice without assistance, they were considered qualified and progressed to the final training stage.

(4) The fourth and final stage was the consolidation stage. Under the guidance of the rehabilitation therapist, patients repeated the full sequence of tasks until they could do it independently in a single, uninterrupted session.

Observation Indicators

Observation indicators assessed during this study were as follows:

(1) General information: These indicators included gender, age, body mass index (BMI), number of coexisting internal diseases, and surgical indications (e.g., traffic accident, hip arthritis, rheumatoid arthritis).

(2) Surgery-related indices: Surgery-related parameters, such as duration of the procedure and total intraoperative blood loss, were recorded.

(3) Hip joint function: Parameters like external and internal rotation, adduction, abduction, extension, and flexion were recorded before training and again at 1, 2, and 4 weeks after training. The sum of these angles calculates the total hip joint range of motion. Furthermore, the moment arm of the hip adductor was evaluated by measuring the distance from the tangent line to the greater trochanter to the perpendicular line through the rotation center of the ipsilateral femoral head before and after training. Similarly, joint functional recovery was determined using the Harris hip score [15], which evaluates deformity, pain, range of motion, and functional status on a 0 to 100 scale, with higher scores indicating better hip function.

(4) Bone metabolism-related markers: Fasting peripheral venous blood samples (4 mL) were collected before training and at weeks 1, 2, and 4 after training to assess serum levels of bone alkaline phosphatase (BALP), type I collagen amino-terminal lengthening peptide (PINP), osteocalcin, type I collagen carboxy-terminal peptide (CTX),

Table 1. Comparison of baseline data and operation-related indicators between the two groups [$\bar{x} \pm$ s, n (%)].

Groups	Observation group (*n* = 45)	Control group (*n* = 52)	t/χ^2 value	*p*-value
Gender			0.275	0.600
Male	30 (66.67)	32 (61.54)		
Female	15 (33.33)	20 (38.46)		
Age (years)	72.96 ± 9.04	72.21 ± 9.57	0.395	0.694
BMI (kg/m^2)	23.01 ± 2.77	23.53 ± 2.88	0.903	0.369
Number of comorbidities			1.052	0.591
1 type	28 (62.22)	27 (51.92)		
2 types	12 (26.67)	18 (34.62)		
3 types	5 (11.11)	7 (13.46)		
Reasons for surgery			0.025	0.988
Traffic accident	23 (51.11)	27 (51.92)		
Hip arthritis	11 (24.44)	12 (23.08)		
Rheumatoid arthritis	11 (24.44)	13 (25.00)		
Surgical side			0.800	0.371
Left	21 (46.67)	29 (55.77)		
Right	24 (53.33)	23 (44.23)		
ASA classification			0.322	0.851
II	27 (60.00)	29 (55.77)		
III	17 (37.78)	21 (40.38)		
IV	1 (2.22)	2 (3.85)		
Duration of surgery (min)	101.72 ± 18.65	103.66 ± 20.43	0.486	0.628
Total blood loss (mL)	262.81 ± 52.36	258.74 ± 61.40	0.348	0.728

BMI, body mass index; ASA, American Society of Anesthesiologists.

intact parathyroid hormone (iPTH), and tartrate-resistant acid phosphatase 5b (TRACP-5b) using a UniCel DxI 800 Automated Chemiluminescence Immunoassay Analyzer (A98264, Beckman Coulter, Inc., Brea, CA, USA). BALP, PINP, and osteocalcin served as bone formation indicators, whereas CTX, iPTH, and TRACP-5b indicated bone resorption.

(5) Quality of life: Patients' functional independence and overall quality of life were assessed before training and at weeks 1, 2, and 4 after training using the Barthel index [16] and the 36-Item Short Form Health Survey (SF-36) [17]. The Barthel Index evaluates 10 activities of daily living, such as bathing, dressing, and eating, with a total score ranging from 0 to 100. A higher score indicates greater independence. The SF-36 scale comprises 8 dimensions across 36 items, with a total score ranging from 0 to 100, where a higher score reflects a better quality of life.

(6) Postoperative complications: The incidence of postoperative complications and adverse events occurring in the first month after surgery were also documented.

Statistical Analysis

Data analysis was performed using SPSS 22.0 software (IBM Corp., Armonk, NY, USA) and GraphPad Prism® 8.0 (GraphPad Software Inc., San Diego, CA, USA). Continuous data underwent normality assessment via the Kolmogorov-Smirnov test. Non-normally distributed data were expressed as median (first quartile - third quartile) and compared between groups using the Mann-Whitney U test. Measurement data following normal distribution were expressed as mean ± standard deviation ($\bar{x} \pm$ s), with comparisons between groups conducted through independent samples *t*-test and within-group comparisons using paired samples *t*-test. Categorical data were represented as n (%) and compared using the χ^2 test. Normality and homogeneity of variance tests for hip joint function and bone metabolism-related markers were determined; if Mauchly's sphericity assumption held, a two-way analysis of variance (ANOVA) was applied, otherwise, the Greenhouse-Geisser correction method was used. Repeated-measures ANOVA was utilized to evaluate time, group, and interaction effects on hip joint function and bone metabolism-related markers during the rehabilitation training. Association between changes in bone metabolism-related markers and variations in Harris hip scores before baseline to week four were assessed using locally weighted scatterplot smoothing (LOWESS). A *p*-value of $<$0.05 indicated statistical significance.

Results

Comparison of Baseline Data and Operation-related Indicators Between the Two Groups

Of the 97 patients, including 62 males and 35 females, aged 45–90 years (mean age 72.56 ± 9.43 years), 50 received surgery after traffic accidents, 23 for hip arthritis, and 24 for rheumatoid arthritis. Comparison of baseline charac-

Table 2. Comparison of hip function recovery before and after rehabilitation training between the two groups [$\bar{x} \pm s$].

Groups	n	Hip joint range of motion (°)			
		Before the training	1st week of the training	2nd week of the training	4th week of the training
Observation group	45	75.69 ± 4.52	91.45 ± 5.02*	118.74 ± 4.88*#	136.78 ± 7.56*#△
Control group	52	76.11 ± 5.09	84.51 ± 5.24*	107.42 ± 6.41*#	121.85 ± 7.94*#△
t value		0.427	6.633	9.666	9.442
p-value		0.671	<0.001	<0.001	<0.001
Group	n	Moment arm of hip abductor muscle (mm)			
		Before the training	1st week of the training	2nd week of the training	4th week of the training
Observation group	45	47.63 ± 2.18	49.25 ± 1.96*	51.87 ± 2.09*#	53.24 ± 1.97*#△
Control group	52	47.51 ± 1.47	48.40 ± 1.44*	49.49 ± 1.77*#	51.75 ± 2.17*#△
t value		0.321	2.455	6.073	3.519
p-value		0.749	0.016	<0.001	0.001
Group	n	Harris hip score (score)			
		Before the training	1st week of the training	2nd week of the training	4th week of the training
Observation group	45	42.75 ± 1.87	51.69 ± 2.72*	59.65 ± 3.01*#	68.54 ± 3.45*#△
Control group	52	42.81 ± 1.91	48.95 ± 2.36*	55.01 ± 2.62*#	60.87 ± 3.03*#△
t value		0.156	5.313	8.118	11.658
p-value		0.887	<0.001	<0.001	<0.001

Compared to before the training, *$p < 0.05$; Compared to 1st week of the training, #$p < 0.05$; Compared to 2nd week of the training, △$p < 0.05$.

teristics and operation-related indicators demonstrated no significant differences in gender, age, BMI, number of comorbidities, reasons for surgery, surgical side, ASA classification, duration of surgery, and total blood loss volume (all $p > 0.05$), indicating that the two groups were comparable (Table 1).

Comparison of Hip Function Recovery Before and After Rehabilitation Training Between the Two Groups

Comparison of hip joint function before training revealed no significant differences in the range of motion, the moment arm of the hip abductor muscle, and Harris hip score between the two groups (all $p > 0.05$). These indicators in both groups increased in weeks 1, 2, and 4 after training, and the observation group showed significantly greater improvements than the control group ($p < 0.05$, Table 2).

Comparison of Osteogenic and Osteoclastic Marker Levels Before and After Rehabilitation Training Between the Two Groups

Analysis of osteogenic and osteoclastic markers between the two groups showed no significant differences in BALP, PINP, osteocalcin, CTX, iPTH, and TRACP-5b levels before training ($p > 0.05$). However, both groups showed progressive increases in BALP, PINP, and osteocalcin at weeks 1, 2, and 4 of the training compared to the baseline levels, with the observation group exhibiting substantially higher levels than the control group ($p < 0.05$). In contrast, the levels of CTX, iPTH, and TRACP-5b decreased sequentially at weeks 1, 2, and 4 in both groups, with the observation group exhibiting greater reductions than the control group ($p < 0.05$, Table 3).

Comparison of Quality-of-life Scores Before and After Rehabilitation Training Between the Two Groups

As detailed in Table 4, a comparison of quality-of-life scores between the two groups revealed no significant baseline differences in Barthel index and SF-36 scores ($p > 0.05$). These scores increased progressively at weeks 1, 2, and 4 than pre-training values, with the observation group demonstrating substantially higher improvements than the control group ($p < 0.05$), as shown in Table 4.

Repeated-measures ANOVA of Hip Function Recovery and Bone Metabolism-related Markers

Assessing normality and homogeneity of variance confirmed that hip range of motion, hip abductor moment arm, Harris hip score, levels of BALP, PINP, osteocalcin, CTX, iPTH, and TRACP-5b all followed a normal distribution with homogeneous variances ($p > 0.05$). Mauchly's sphericity assumption test revealed that the variance-covariance matrices of these indicators were equal (χ^2 = 3.241, 5.065, 4.212, 2.189, 4.043, 1.188, 2.372, 3.064, 4.288; p = 0.652, 0.373, 0.428, 0.702, 0.436, 0.802, 0.695, 0.672, 0.416). Repeated-measures ANOVA revealed substantial time, group, and time-by-group interaction effects for all indicators during the training period ($p < 0.05$, Table 5 and Fig. 2).

Correlation Between Changes in Bone Metabolism-related Markers Levels and the Corresponding Changes in Harris Hip Scores

The LOWESS analysis showed a non-linear relationship between difference values in bone metabolism-related markers (BALP, PINP, osteocalcin, CTX, iPTH, and TRA-

Table 3. Comparison of osteogenic and osteoclastic marker levels between the two groups before and after rehabilitation training [$\bar{x} \pm$s].

Group	n	BALP (U/L)				PINP (ng/mL)			
		Before the training	1st week of the training	2nd week of the training	4th week of the training	Before the training	1st week of the training	2nd week of the training	4th week of the training
Observation group	45	14.72 ± 2.64	17.31 ± 2.96*	$20.16 \pm 2.21^{*\#}$	$23.25 \pm 2.71^{*\#\triangle}$	69.64 ± 5.65	75.74 ± 5.86*	$81.28 \pm 6.25^{*\#}$	$90.37 \pm 6.32^{*\#\triangle}$
Control group	52	14.64 ± 2.52	15.97 ± 2.11*	$18.29 \pm 2.16^{*\#}$	$20.81 \pm 3.05^{*\#\triangle}$	69.41 ± 5.79	73.11 ± 5.92*	$76.97 \pm 6.14^{*\#}$	$84.56 \pm 6.43^{*\#\triangle}$
t value		0.153	2.592	4.207	4.136	0.197	2.192	3.419	4.473
p-value		0.879	0.011	<0.001	<0.001	0.844	0.031	0.001	<0.001

Group	n	Osteocalcin (μg/L)				CTX (pg/mL)			
		Before the training	1st week of the training	2nd week of the training	4th week of the training	Before the training	1st week of the training	2nd week of the training	4th week of the training
Observation group	45	13.68 ± 1.89	16.47 ± 2.01*	$18.89 \pm 2.18^{*\#}$	$21.02 \pm 2.21^{*\#\triangle}$	536.95 ± 21.47	497.42 ± 21.17*	$459.85 \pm 20.48^{*\#}$	$414.83 \pm 19.18^{*\#\triangle}$
Control group	52	13.57 ± 1.76	15.15 ± 1.94*	$17.09 \pm 2.11^{*\#}$	$17.57 \pm 2.15^{*\#\triangle}$	534.84 ± 20.65	516.24 ± 21.06*	$488.73 \pm 20.85^{*\#}$	$432.91 \pm 20.79^{*\#\triangle}$
t value		0.297	3.286	4.126	7.780	0.493	4.379	6.859	4.427
p-value		0.767	0.001	<0.001	<0.001	0.623	<0.001	<0.001	<0.001

Group	n	iPTH (pg/mL)				TRACP-5b (U/L)			
		Before the training	1st week of the training	2nd week of the training	4th week of the training	Before the training	1st week of the training	2nd week of the training	4th week of the training
Observation group	45	52.36 ± 5.98	45.28 ± 5.73*	$41.05 \pm 5.12^{*\#}$	$35.26 \pm 4.62^{*\#\triangle}$	6.10 ± 0.51	5.21 ± 0.45*	$4.56 \pm 0.37^{*\#}$	$3.72 \pm 0.24^{*\#\triangle}$
Control group	52	52.24 ± 6.05	48.92 ± 5.46*	$45.31 \pm 5.24^{*\#}$	$40.05 \pm 4.39^{*\#\triangle}$	6.02 ± 0.47	5.67 ± 0.41*	$5.07 \pm 0.28^{*\#}$	$4.16 \pm 0.30^{*\#\triangle}$
t value		0.098	3.200	4.036	5.230	0.804	5.267	7.712	7.892
p-value		0.922	0.002	<0.001	<0.001	0.424	<0.001	<0.001	<0.001

BALP, bone alkaline phosphatase; PINP, type I collagen amino-terminal lengthening peptide; CTX, type I collagen carboxy-terminal peptide; iPTH, intact parathyroid hormone; TRACP-5b, tartrate-resistant acid phosphatase 5b; Compared to before the training, $^{*}p < 0.05$; Compared to 1st week of the training, $^{\#}p < 0.05$; Compared to 2nd week of the training, $^{\triangle}p < 0.05$.

Table 4. Comparison of quality-of-life scores before and after rehabilitation training between the two groups [$\bar{x} \pm s$].

Group	n	Barthel index score			
		Before the training	1st week of the training	2nd week of the training	4th week of the training
Observation group	45	53.87 ± 4.39	67.95 ± 5.14*	81.42 ± 6.18*#	89.56 ± 6.95*#△
Control group	52	54.04 ± 4.45	61.42 ± 5.29*	72.53 ± 6.39*#	80.44 ± 7.15*#△
t value		0.189	6.143	6.938	6.346
p-value		0.851	<0.001	<0.001	<0.001
Group	n	SF-36 scores (point)			
		Before the training	1st week of the training	2nd week of the training	4th week of the training
Observation group	45	72.31 ± 5.45	86.25 ± 5.96*	91.37 ± 4.82*#	95.11 ± 4.21*#△
Control group	52	72.47 ± 5.33	80.49 ± 6.15*	86.89 ± 4.44*#	91.5 ± 4.58*#△
t value		0.146	4.666	4.763	4.018
p-value		0.884	<0.001	<0.001	<0.001

SF-36, 36-Item Short Form Health Survey; Compared to before the training, $^{*}p < 0.05$; Compared to 1st week of training, $^{\#}p < 0.05$; Compared to 2nd week of the training, $^{\triangle}p < 0.05$.

CP-5b) over the 4 weeks of training and difference values in Harris hip scores from the baseline to week 4 (Fig. 3).

Incidence of Postoperative Complications Among the Patients

In the observation group, postoperative complication rates were as follows: deep vein thrombosis (DVT) 0.00% (0/45), pressure injuries 2.22% (1/45), infections 0.00% (0/45), muscle atrophy 2.22% (1/45), joint stiffness 2.22% (1/45), and overall complications 6.67% (3/45). The corresponding rates in the control group were 1.92% (1/52), 3.85% (2/52), 1.92% (1/52), 3.85% (2/52), 3.85% (2/52), and 15.38% (8/52), respectively. No statistically significant difference was observed in the overall complication rate between the two groups (χ^2 = 1.824, p = 0.177).

Discussion

With advancing age and an increasingly aging population, bone density in the human body gradually declines, leading to an increasing annual incidence of hip fractures, which are associated with high mortality rates [18–20]. HA is a surgical procedure that replaces a dysfunctional joint with a prosthesis, offering significant pain relief. However, postoperative self-care, activities of daily living, and social participation require improvement [21–24]. Currently, rehabilitation guidance in patients undergoing HA relies on video and verbal instruction, resulting in insufficient patient mastery of required rehabilitation knowledge. This limitation hampers optimal recovery of daily living skills and fails to achieve the expected surgical outcomes [25,26]. Therefore, high-quality postoperative rehabilitation training is crucial for hip disease treatment, as it enhances muscle strength, reduces swelling, minimizes complications, and promotes functional recovery. With the widespread adoption of enhanced rehabilitation protocols, there is an elevated clinical focus on optimizing postoperative function. Therefore, this study applies a stepped rehabilitation training approach to explore its effects on functional recovery in patients following HA.

Effect of Stepped Rehabilitation Training on Restoring Hip Joint Function

Restoring hip function is a critical goal of postoperative rehabilitation after HA. A study by Meng *et al.* [27] showed that a 6-month self-efficacy enhancement yielded excellent Harris hip scores (90.52 ± 4.03) among total HA patients. Similarly, Bao *et al.* [10] found that stepped, simulated home-based rehabilitation training significantly improved Harris hip scores and promoted postoperative functional recovery.

In the current study, patients who received stepped rehabilitation training demonstrated higher hip range of motion, abductor muscle strength, and Harris hip scores compared to those undergoing conventional rehabilitation exercises, with all metrics progressively improving over time. These findings indicate that a sequential, targeted strengthening of muscle groups, coupled with progressive improvement in joint flexibility and stability, effectively promotes functional recovery after HA. This training pattern not only focuses on early pain management and basic functional reconstruction but also gradually incorporates advanced exercises such as gait training, balance training, and simulation of functional activities, thereby holistically enhancing the patients' hip functions. This training approach significantly enhances hip joint recovery, improves patient's self-care capabilities, reduces the incidence of complications, and increases satisfaction with surgical outcomes.

Effect of Stepped Rehabilitation Training on Bone Metabolic Markers

BALP, PINP, and osteocalcin are markers of bone formation metabolism, whereas CTX, iPTH, and TRACP-5b reflect bone resorption. Changes in these indicators reflect the activity, equilibrium, and overall health of skeletal metabolism [28–30]. Yan and Zhang [31] reported that ad-

Table 5. Repeated measures of variance analysis of hip function and bone metabolism-related markers during training between the two groups [$\bar{x} \pm s$].

Indicators	Time effect		Inter-group effect		Interaction effect	
	F	*p*	*F*	*p*	*F*	*p*
Hip joint range of motion (°)	469.522	<0.001	95.727	<0.001	70.824	<0.001
Moment arm of hip abductor muscle (mm)	188.461	<0.001	18.6424	<0.001	7.418	0.001
Harris hip score (point)	573.432	<0.001	146.793	<0.001	128.521	<0.001
BALP (U/L)	102.483	<0.001	7.418	0.001	6.437	0.009
PINP (ng/mL)	76.645	<0.001	5.241	0.010	4.726	0.026
Osteocalcin (μg/L)	247.314	<0.001	62.740	<0.001	41.185	<0.001
CTX (pg/mL)	209.566	<0.001	39.266	<0.001	20.729	<0.001
iPTH (pg/mL)	156.390	<0.001	9.043	<0.001	5.038	0.011
TRACP-5b (U/L)	328.163	<0.001	74.655	<0.001	52.464	<0.001

BALP, bone alkaline phosphatase; PINP, type I collagen amino-terminal lengthening peptide; CTX, type I collagen carboxy-terminal peptide; iPTH, intact parathyroid hormone; TRACP-5b, tartrate-resistant acid phosphatase 5b.

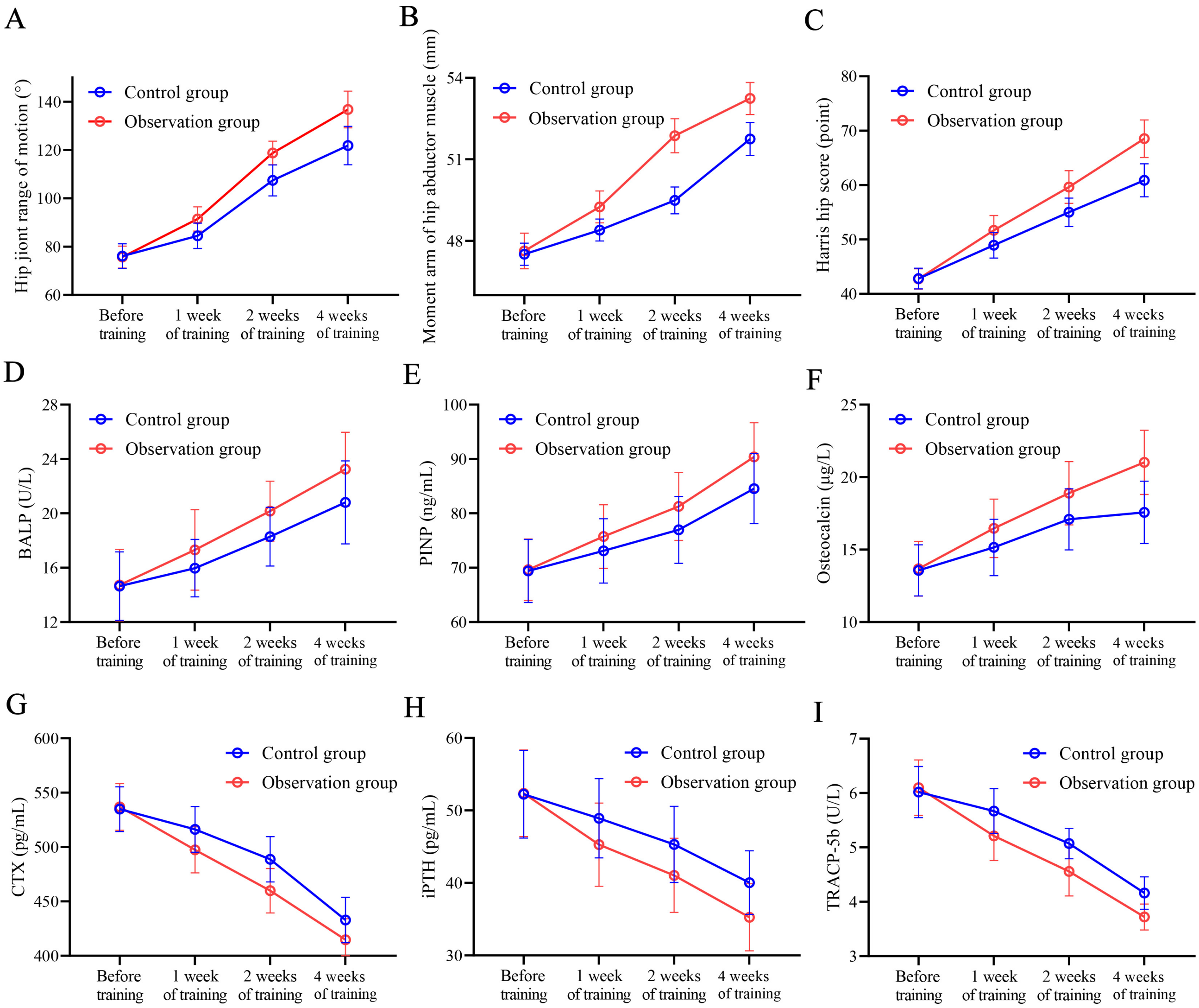

Fig. 2. Interaction between hip range of motion (A), hip abductor moment arm (B), Harris hip score (C), levels of BALP (D), PINP (E), osteocalcin (F), CTX (G), iPTH (H), and TRACP-5b (I) and groups at different time points in the two groups. BALP, bone alkaline phosphatase; PINP, type I collagen amino-terminal lengthening peptide; CTX, type I collagen carboxy-terminal peptide; iPTH, intact parathyroid hormone; TRACP-5b, tartrate-resistant acid phosphatase 5b. The figure was created with GraphPad Prism® 8.0 (GraphPad Software Inc., San Diego, CA, USA).

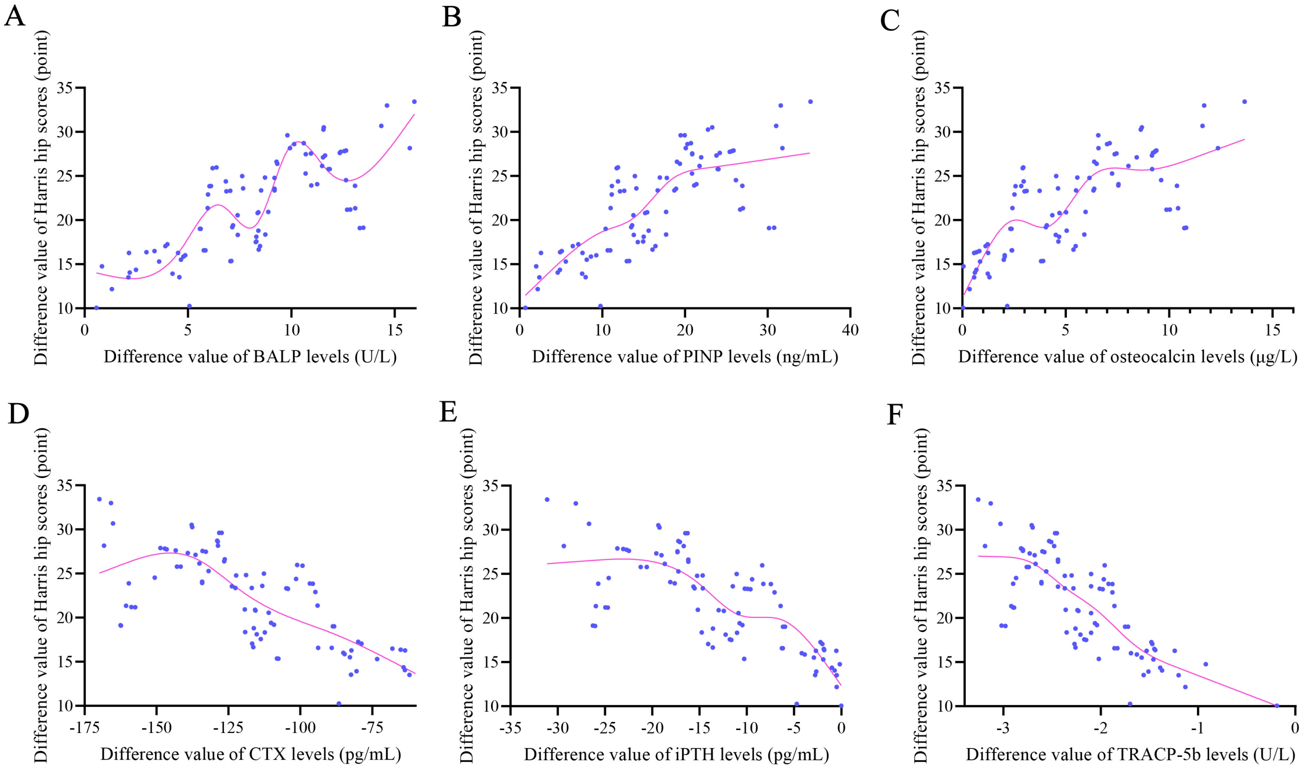

Fig. 3. LOWESS analysis of the association between pre- and post-training difference values in the levels BALP (A), PINP (B), osteocalcin (C), CTX (D), iPTH (E) and TRACP-5b (F) and difference in Harris hip scores. BALP, bone alkaline phosphatase; PINP, type I collagen amino-terminal lengthening peptide; CTX, type I collagen carboxy-terminal peptide; iPTH, intact parathyroid hormone; TRACP-5b, tartrate-resistant acid phosphatase 5b. The figure was created with GraphPad Prism® 8.0 (GraphPad Software Inc., San Diego, CA, USA).

ministering a bone-injury recovery decoction after HA in patients with femoral neck fracture significantly increased the levels of BALP, PINP, and osteocalcin while decreasing TRACP-5b.

In our study, stepped rehabilitation training after HA showed greater improvement in BALP, PINP, and osteocalcin compared with conventional care and exercises. These results indicate that stepped rehabilitation training improves osteoblast activity and increases the synthesis of bone formation proteins while inhibiting osteoclast activity and reducing bone resorption markers. This positive modulation of bone metabolism is crucial for preventing postoperative osteoporosis and promoting fracture healing. Therefore, physicians should monitor these indicators during postoperative rehabilitation and tailor the training program to individual situation to promote rapid joint function recovery.

Effects of Rehabilitation Training on Quality of Life

Restoration of hip joint function is closely corelated to a patient's capability for daily activities and overall independence [32]. In our study, quality of life was evaluated through the Barthel index and SF-36 scale. The results showed that both patient groups showed significant improvements in the quality of life, but the enhancement was more pronounced in the stepped rehabilitation training cohort. This indicates that stepped rehabilitation training not only enhances hip range of motion and muscle strength, enabling smoother performance of various daily activities, but also improves overall quality of life by enhancing physical fitness, reducing pain, and increasing functional autonomy. Such multifaceted advantages support more comprehensive recovery and greater social participation. Furthermore, quality of life scores elevated sequentially at weeks 1, 2, and 4, highlighting the impact of rehabilitation training and its sustained advantages over time. By improving functional capacity and psychological well-being, stepped rehabilitation training alleviates family burdens and promotes their mental health.

The repeated-measures ANOVA demonstrated that stepped rehabilitation training significantly improved hip joint function and bone metabolism markers, with notable time, group, and interaction effects (all $p < 0.05$). Clinically, these findings highlight several crucial points. First, the time effects confirm the cumulative benefits of rehabilitation intervention, supporting the scientific rationale for a phased, progressive training protocol. Second, the significant between-group effects indicate that stepped training outperforms conventional rehabilitation in promoting functional recovery and optimizing bone metabolism. Most importantly, the interaction effects suggest faster recovery rates in the stepped training group, supporting the development of individualized rehabilitation programs. Based on these results, we recommend implementing more intensive rehabilitation during the early postoperative period and regularly monitoring bone metabolism markers to guide training adjustments, thereby optimizing rehabilitation outcomes. These findings provide strong, evidence-based guidance for optimizing post-hip arthroplasty rehabilitation.

Furthermore, LOWESS analysis demonstrated complex, nonlinear relationships between the changes in Harris hip score (ΔHarris) and the variations in bone metabolism markers (ΔBALP, ΔPINP, Δosteocalcin, ΔCTX, ΔPTH, and ΔTRACP-5b) after rehabilitation training. Rather than demonstrating a linear relationship, the enhancement rate in ΔHarris may fluctuate, accelerate, or decelerate as each marker changes. For example, a small increase in ΔBALP might lead to gradual gains in ΔHarris up to a point beyond which further increases in ΔBALP could induce rapid score enhancement, or even temporary decrease. Similarly, complex nonlinear associations may exist for ΔPINP and Δosteocalcin. This finding implies that linear regression models alone cannot reflect the actual dynamics between bone-related indicators and functional recovery. Future studies should explore the underlying mechanisms driving nonlinear relationships, accounting for interactions among multiple factors, to better understand the rehabilitation training's impact on bone health and functional recovery.

The results of our study demonstrated that the overall postoperative complication rate was lower in the observation group (6.67%) compared to the control group (15.38%), although this difference did not achieve statistical significance (p = 0.177). Clinically, the stepped rehabilitation training group showed a substantial reduction in complications such as deep vein thrombosis (0% vs 1.92%) and surgical-site infections (0% vs 1.92%). These protective effects may be attributed to the phased, progressive training protocol: early bedside mobilization promotes venous return, standardized movement training reduces wound stress, and systematic muscle strengthening enhances joint stability. While the statistical power may have been limited by sample size, the findings suggest that stepped rehabilitation could exert protective effects through improved hemodynamics and enhanced tissue repair. Future studies with larger sample sizes are warranted to validate their efficacy in preventive-specific postoperative complications.

Research Limitations and Future Prospects

Despite the promising outcomes of this study, we acknowledge several limitations. Firstly, the sample size was relatively small; future research should include more patients to enhance the generalizability of the results. Secondly, this study was limited to short-term outcomes of rehabilitation training; longer follow-up data is needed to comprehensively assess long-term benefits. Finally, this study did not compare stepped rehabilitation training with alternative protocols; future research should focus on conducting comparative studies to determine the optimal postoperative rehabilitation approach for patients following hip arthroplasty.

Conclusions

In summary, repeated-measures ANOVA confirmed the positive effects of stepped rehabilitation training on the recovery of hip joint function, improvement of bone metabolism markers, and enhancement of quality of life in patients undergoing HA. Future studies should comprehensively investigate the mechanisms underlying these advantages and optimize rehabilitation programs to enhance patient outcomes.

Availability of Data and Materials

All experimental data included in this study can be obtained by contacting the corresponding author if needed.

Author Contributions

TZ designed the study framework, established methodologies, and outlined experimental protocols to ensure research feasibility and rigor. XPL contributed to data collection (e.g., experiments, surveys) and curation; YZ conducted formal statistical analysis and visualization to generate interpretable results. All authors contributed to drafting. LL contributed to the conceptualization of data interpretation framework, participated in methodological design validation, and refined the text through iterative revisions, ensuring logical flow and academic integrity. CYH conceived the original research question, supervised experimental design and progress, provided critical intellectual input during manuscript revision, and ensured ethical compliance and resource management. LJ validated methodologies and cross-verified key findings to guarantee robustness. All authors contributed to important editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study was conducted following the principles of the Declaration of Helsinki and was approved by the Ethics Committee of Shanghai Baoshan District Wusong Central Hospital (Approval No. 2023-4). Written informed consent was obtained from all participants.

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Conflict of Interest

The authors declare no conflict of interest.

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