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Functional recovery of athletes through rehabilitation training after anterior cruciate ligament reconstruction

Research Article

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Abstract
Purpose: This article aims to introduce neuromuscular electrical stimulation into rehabilitation training after anterior cruciate ligament reconstruction and to assess its impact on the functional recovery of the knee joint.
Methods: Twenty athletes undergoing anterior cruciate ligament reconstruction were allocated into a neuromuscular electrical stimulation group (neuromuscular electrical stimulation + rehabilitation training) and a conventional group (conventional rehabilitation training) for a 10-week training program. Indicators such as Lysholm scores and thigh circumference were assessed before and after training for comparison.
Results: After training, the neuromuscular electrical stimulation group demonstrated a Lysholm score of 86.56 ± 11.67 points, a thigh circumference on the affected side of 47.15 ± 2.56 cm, and an active knee flexion angle of 105.12 ± 9.87°. Moreover, the score of the *Y*-balance test under left- and right-foot support was 93.67 ± 0.43 and 91.72 ± 0.48 points, respectively. It achieved a 10-meter walk speed of 1.01 ± 0.15 m/s. It achieved a performance of 264.39 ± 29.36 cm in three consecutive single-leg jumps on the healthy side and a performance of 178.16 ± 21.26 cm on the affected side. Its anterior cruciate ligament return-to-sport after injury scale score was 84.21 ± 5.32 points. These outcomes were significantly superior to those of the conventional group.
Conclusions: Neuromuscular electrical stimulation combined with rehabilitation training yields positive effects on functional recovery after anterior cruciate ligament reconstruction, surpassing the outcomes of conventional rehabilitation training. This approach holds promise for practical application.

Keywords: *Rehabilitation training • Anterior cruciate ligament reconstruction • Functional recovery • Knee joint*

1. Introduction

Knee injuries are a common occurrence among athletes [1], and anterior cruciate ligament (ACL) injuries are a particularly severe type of knee injury and prevalent in sports such as basketball, soccer, and skiing [2]. ACL injuries can significantly impact knee joint function, resulting in symptoms such as swelling and instability [3]. ACL reconstruction is a treatment for ACL injuries [4], and its post-surgical recovery is important. Hsu et al. [5] explored the effects of progressive resistance training on kinematics, kinetics, and muscle strength in patients with anterior cruciate ligament reconstruction (ACLR). They found that this training could significantly improve the symmetry of knee extensors, the vertical jump height of a single leg, and the maximum knee flexion angle after landing, and it was superior to the control group in all indicators. Curley et al. [6] analyzed the effectiveness of early use of blood flow restriction training (BFRT) combined with low-intensity exercises in the rehabilitation period following ACLR. Through a randomized controlled trial, they found that BFRT might accelerate the rehabilitation after ACLR, improve quadriceps strength, and relieve postoperative pain. Niederer et al. [7] explored the effects of neuromuscular performance intervention (Stop-X) on late-stage recovery following ACLR, reporting increased

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confidence in returning to the sport, reduced knee-related pain issues, and improved daily activity performance in the Stop-X group. Ananias et al. [8] investigated the use of electromyographic biofeedback in ACLR rehabilitation. Through systematic review and meta-analysis, it was found that electromyographic biofeedback can improve knee extension and balance. Postoperative rehabilitation training has a great impact on the functional recovery of the knee joint [9]. Neuromuscular electrical stimulation (NMES), a rehabilitation technique that involves stimulating muscle groups via electrodes to induce muscle contractions and enhance functional recovery, has been widely used in the rehabilitation field [10]. This study introduced NMES into post-ACLR rehabilitation training to examine its impact on post-ACLR functional recovery in athletes, providing a theoretical foundation for ACLR rehabilitation and some references for future applications of NMES in sports rehabilitation.

2. Materials and methods

2.1 Study subjects

Athletes who attended an orthopedic hospital in Hainan Province and underwent ACLR from 2023 to 2024 were used as experimental subjects, and the specific screening criteria were as follows:

(1) Inclusion criteria
① Unilateral knee ACL injury caused by sports;
② Positive drawer test and Lachman test results [11], with ACL injuries confirmed by magnetic resonance imaging;
③ Undergoing arthroscopic autologous hamstring tendon reconstruction of ACL completed by the same physician;
④ Sign the informed consent.

(2) Exclusion criteria
① History of previous ACL injury;
② Presence of other knee injuries;
③ Serious postoperative complications such as infection;
④ Serious cardiopulmonary disease or combination of fractures in other parts of the body;
⑤ Inability to obey the training arrangement.

(3) Dropout criteria
① Re-injury during the experiment;
② Unable to adapt to rehabilitation training;
③ Take the initiative to withdraw.

Table 1. Basic information of athletes

	NMES group (n = 10)	Conventional group (n = 10)
Gender	Male = 4, Female = 6	Male = 5, Female = 5
Age, year	21.23 ± 1.68	21.26 ± 1.71
Height, cm	175.62 ± 5.68	176.15 ± 6.02
Weight, kg	72.36 ± 12.36	73.29 ± 11.78
Training time, year	5.69 ± 2.23	5.77 ± 2.19

Based on the aforementioned criteria, a total of 20 eligible athletes were included in the study and randomly divided into two groups. The first group underwent rehabilitation training supplemented with NMES, referred to as the NMES group. In contrast, the second group received only conventional rehabilitation training, designated as the conventional group. The baseline characteristics of the participants are presented in Table 1, showing no statistically significant differences ($p > 0.05$), i.e., the results were comparable.

2.2 Rehabilitation training program

After ACLR, the effectiveness of conventional rehabilitation training is often limited due to pain, swelling, and nerve control disorders. As a noninvasive peripheral intervention, NMES can activate the peripheral nerves that innervate the target muscles through electrical pulses, triggering involuntary muscle contractions, thereby breaking muscle inhibition. That is to say, NMES can make up for the limitations of conventional rehabilitation training and is easy to implement clinically. Li et al. [12] found through a systematic review and meta-analysis that for quadriceps weakness after ACL surgery, rehabilitation using NMES can significantly enhance the strength of the quadriceps compared with simple rehabilitation. Currently, there are still relatively few studies on the rehabilitation training effect of NMES after ACLR. The synergistic effect of NMES in the systematic rehabilitation of ACLR athletes still requires high-quality evidence support. Therefore, it is necessary to further prove the role of NMES through experiments. For this reason, this article selects NMES on the basis of conventional rehabilitation training. Both groups of athletes participated in a 10-week rehabilitation training program, starting from the 3rd week postoperatively and ending at the 12th week postoperatively. The conventional group followed the Postoperative Orthopedic Rehabilitation Guidelines for their rehabilitation training (Table 2).

Table 2. Rehabilitation training program for the conventional group

Time	Content	Number of groups
Week 2–6 after surgery	Walking exercise	10–15 min for each exercise, twice each day
	Resistance straight-leg raising exercise and weight transfer exercise	
	Stair climbing exercise	
	Weighted knee extension exercise	
	Elastic band-assisted leg curl exercise	
Week 6–12 after surgery	Static squatting exercise	10–15 min for each exercise, twice each day
	Stair descending exercise	
	Split-leg squatting exercise	
	Balance exercise	

The NMES group utilized the Compex Neuromuscular Electrical Stimulator 8.0 for training, five times a week, each lasting 120 min (Table 3).

2.3 Functional recovery indicator tests

(1) Lysholm score [13]
Test method: athletes filled out the Lysholm scale to assess knee function.
Test time: before and after rehabilitation training.

(2) The thigh circumference of the affected side
Test method: athletes lay on their backs on a hospital bed. A mark was made at 15 cm above the midpoint of the patella, and the thigh circumference was measured using a tape measure. This process was repeated three times, and the average value was calculated.
Testing time: before and after rehabilitation training.

(3) Active knee flexion angle of the affected side
Test method: athletes lay prone on the hospital bed and actively flexed the knee of the affected side. The joint angle was measured using a protractor, with the stationary arm parallel to the femoral long axis, the fulcrum centered on the fibular head, and the movable arm parallel to the fibular long axis. Angle data were subsequently recorded. This process was repeated three times, and the average value was calculated.
Test time: before and after rehabilitation training.

(4) *Y*-balance test [14]
Test method: athletes stood with one foot in the center of the *Y*-balance test instrument while pushing the opposite foot out to the front, rear medial, and rear lateral sides. The distances in each direction were recorded. This process was repeated three times, and the best performance was taken.
Test time: after rehabilitation training.

(5) 10-m walk
Test method: athletes stood at the starting point of a 10-meter track and began walking upon hearing the starting cue. The timer started counting when the toe of the foot crossed the 2-m mark and stopped when the toe crossed the 8-m mark. This process was repeated three times, and the best performance was recorded.
Test time: after rehabilitation training.

(6) Three consecutive jumps on one leg
Test method: athletes stood at the starting point and performed three consecutive single-leg jumps with both the affected leg and the healthy leg. The distance jumped was recorded. This process was repeated three times, and the best performance was taken.
Test time: after rehabilitation training.

(7) ACL return-to-sport after injury (ACL-RSI) scale [15]
Test method: athletes filled out the ACL-RSI scale to assess their psychological status after returning to sport.
Testing time: after rehabilitation training.

2.4 Statistical analysis

The test results were recorded as mean ± standard deviation, and statistical analysis was conducted using SPSS 20.0. Intergroup comparisons were analyzed using an independent samples *t*-test [16], while intragroup comparisons were analyzed using a paired samples *t*-test [17], with a significance level set at 0.05.

3. Results

Table 4 shows no significant difference in the baseline scores between the NMES group and the conventional group, indicating comparability before the intervention.

Table 3. Rehabilitation program for the NMES group

Time	Content	Program	Position of electrical stimulation patch	Duration, min
Week 2–4 after surgery	Knee mobility training	Sliding wall exercise	The front of the thigh	5
		Knee flexion and extension exercises	The front of the thigh	25
	Leg muscle strength training	Squatting	The front of the thigh	20
		Prone backward and upward calf curl exercise	The back of the thigh	20
		Seated resistance bicycle exercise	The front of the thigh	15
		Squatting against the wall	The front of the thigh	5
	Functional training for adjacent joints	Prone leg raise exercise	Hip	10
		Standing heel raise exercise	Calf gastrocnemius	10
		Core exercise	Lower back and abdominals	10
Week 4–8 after surgery	Knee mobility training	Seated resistance bicycle exercise	The front of the thigh	30
	Leg muscle strength training	Lunge squat exercise	The front of the thigh	20
		Bridge leg curl exercise	The back of the thigh	20
		Squatting against the wall	The front of the thigh	10
	Functional training for adjacent joints	Hip bridge exercise	Hip	20
		Heel lifts	Calf gastrocnemius	10
		Core exercise	Lower back and abdominals	10
Week 8–12 after surgery	Knee mobility training	Seated resistance bicycle exercise	The front of the thigh	30
	Leg muscle strength training	Lunge squat exercise	The front of the thigh	20
		Supine suspension knee curl	The back of the thigh	20
		Squatting against the wall	The front of the thigh	10
	Functional training for adjacent joints	Weighted hip bridge exercise	Hip	20
		Weighted heel lift	Calf gastrocnemius	20
		Core exercise	Lower back and abdominals	10

Table 4. Comparison of Lysholm scores

	Before training	After training	*P* value	Cohen's *d*
NMES group	19.56 ± 5.87	86.56 ± 11.67	0.001	7.61
Conventional group	19.89 ± 5.64	74.12 ± 12.03	0.001	6.16
P value	0.146	0.026		
Cohen's *d*	0.06	1.05		

After the intervention, the scores of both groups were significantly higher than those before the training, and the effect size between the groups was extremely large. The intergroup comparison showed that the Lysholm score of the NMES group after training was significantly higher and that the effect size between the groups was large.

Table 5 also shows an insignificant difference in the circumference between the two groups before training. After training, the thigh circumference of the NMES group increased significantly compared to before training, and the intergroup effect size was extremely large. The intergroup comparison showed that the thigh circumference of the NMES group after training was

Table 5. Comparison of thigh circumference on the affected side (unit: cm)

	Before training	After training	*P* value	Cohen's *d*
NMES group	42.36 ± 2.68	47.15 ± 2.56	0.001	1.83
Conventional group	43.01 ± 2.94	43.26 ± 2.77	0.069	0.09
P value	0.089	0.044		
Cohen's *d*	0.23	1.46		

significantly larger, and the intergroup effect size was extremely large.

Table 6 suggests no significant difference in the angles between the two groups before training. After training, the active flexion angle of the affected knee joint in the NMES group increased significantly compared to before training, and the intergroup effect size was extremely large. The intergroup comparison demonstrated that the active flexion angle of the affected knee joint in the NMES group was significantly larger than that in the conventional group after training, and the intergroup effect size was large.

In Table 7, the *Y*-balance test performance of the NMES group was significantly higher than that of the conventional group, and the effect size between the groups was extremely large. There were no significant differences in the performance within the NMES group and the conventional group between the two support conditions.

As shown in Table 8, the 10-m walking speed of the NMES group was significantly faster than that of the conventional group, and the effect size between the groups was extremely large.

In Table 9, there was no significant difference between the two groups in the healthy-side jump. In the affected-side jump, the performance of the NMES group was significantly better than that of the conventional group, with a large effect size between the groups. The intragroup comparison showed that the performance of the healthy

Table 6. Active flexion angle of the affected knee joint (unit: °)

	Before training	After training	*P* value	Cohen's *d*
NMES group	28.79 ± 8.94	105.12 ± 9.87	0.001	8.11
Conventional group	28.16 ± 8.69	90.21 ± 18.64	0.003	4.48
P value	0.084	0.018		
Cohen's *d*	0.07	1.01		

Table 7. *Y*-balance test performance

	NMES group	Conventional group	*P* value	Cohen's *d*
Left-leg support	93.67 ± 0.43	84.46 ± 0.56	0.002	8.21
Right-leg support	91.72 ± 0.48	83.37 ± 0.62	0.001	8.33
P value	0.067	0.082		
Cohen's *d*	0.05	0.07		

Table 8. Ten-meter walking speed (unit: m/s)

	NMES group	Conventional group	*P* value	Cohen's *d*
Ten-meter walking speed	1.01 ± 0.15	0.84 ± 0.12	0.001	5.56

Table 9. Comparison of three consecutive jumps on one leg (unit: cm)

	NMES group	Conventional group	*P* value	Cohen's *d*
Healthy side	264.39 ± 29.36	261.37 ± 29.87	0.067	0.11
Affected side	178.16 ± 21.26	150.36 ± 30.77	0.033	1.05
P value	0.002	0.003		
Cohen's *d*	8.77	5.45		

Table 10. Comparison of ACL-RSI scale scores

	NMES group	Conventional group	*P* value	Cohen's *d*
ACL-RSI scale score	84.21 ± 5.32	68.97 ± 4.17	0.001	7.64

side was better than that of the affected side in both groups, and the intragroup effect was extremely large.

As shown in Table 10, the ACL-RSI scale score of the NMES group was significantly higher than that of the conventional group, and the effect size between the groups was extremely large.

4. Discussion

Joint pain and functional limitations are common after ACLR [18]. For athletes who want to return to the playing field as soon as possible, the rehabilitation training after ACLR is particularly important [19]. The goal of rehabilitation after ACLR is to help the transplanted ligaments adapt to the athlete's body environment and restore the function of the knee joint.

The Lysholm score can comprehensively evaluate the knee joint function after ACLR [20]. After ACLR, due to inflammation, limited mobility, and other factors, there will be a certain degree of atrophy in the muscles around the knee joint [21]. Measuring the thigh circumference can reflect the recovery status of the thigh muscles. After ACLR, the internal environment of the knee joint is disrupted. Under the influence of inflammation, the range of motion of the knee joint is restricted [22]. The *Y*-balance test can well reflect the body's dynamic balance ability. It is applied in the assessment of ankle instability and other conditions and can effectively reflect the flexibility and stability of joints. Walking speed reflects the body's walking function. After ACLR, under the influence of joint pain and decreased control ability, the body's gait will be abnormal [23], and the walking speed will slow down. Jumping ability is also an important function of the human body, and the ACL-RSI scale score can reflect the athletes' confidence in returning to sports. The experimental results demonstrated that the NMES group showed significant advantages in multiple functional indicators. This finding is somewhat similar to the research conclusions in existing literature regarding the role of NMES in post-orthopedic surgery rehabilitation.

The research by Mintken et al. [24] shows that early postoperative NMES can relieve quadriceps weakness after total knee arthroplasty (TKA). Compared with single rehabilitation training, it can more effectively reduce the loss of quadriceps torque. The research by Delanois et al. [25] also indicates that receiving NMES after TKA can significantly relieve pain and improve knee joint function. Durigan et al. [26] evaluated the effect of NMES on the extracellular matrix remodeling of the quadriceps femoris after ACL disruption in rats and proved the benefits of NMES. Zhang et al. [27] evaluated the role of NMES in post-shoulder surgery rehabilitation and found that NMES has advantages in pain management. Windley [28] pointed out that NMES can be used as an effective tool to enhance the muscle strength of athletes during orthopedic injury rehabilitation. The results of this study showed that the NMES group achieved significantly better results than the conventional group in terms of Lysholm score, thigh circumference, and knee joint range of motion, which further verifies the role of rehabilitation training combined with NMES and also demonstrates the effectiveness of this training program in the rehabilitation of athletes after ACLR.

However, this study also has some limitations. For example, the small sample size restricted the generalizability of the research results. The individualized optimization of NMES parameters, such as frequency and pulse width, was not explored in depth in the research, which

affects the maximization of the intervention effect. Moreover, the follow-up time was short, resulting in a lack of medium- and long-term follow-up data. It is unclear whether the rehabilitation protocol combined with NMES can bring more lasting curative effects, and the potential physiological mechanism of the curative effect produced by NMES was not explored in depth. Therefore, in future work, these aspects need to be improved to further explore the curative effect of NMES on knee joint function recovery.

5. Conclusion

This study examined the impact of combining NMES with rehabilitation training on post-ACLR knee function recovery in athletes. After 10 weeks of rehabilitation, it was observed that the NMES group exhibited a higher Lysholm score, an improved thigh circumference, an increased knee flexion angle, an improved balance and walking ability, a better jumping ability, and a higher ACL-RSI scale score compared to the conventional group. These findings highlight the positive impact of NMES in combination with rehabilitation training on functional recovery, suggesting its application potential in rehabilitation programs.

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Author contributions

Jin Du contributed the central idea, analysed most of the data, and wrote the initial draft of the paper. Haoyan Liu contributed to refining the ideas, carrying out additional analyses, and finalizing this paper.

Conflict of interest statement

Authors state no conflict of interest.

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