Effects of Supervised Plyometric Training on Neuromuscular and Knee Functions for Late Phase Rehabilitation Program in Patients with Anterior Cruciate Ligament Reconstruction: A Randomized Controlled Trial

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ABSTRACT

Objective: To determine the effects of plyometric training programs on neuromuscular and knee functions during the late phase rehabilitation following anterior cruciate ligament (ACL) reconstruction.

Materials and Methods: Thirty participants, post-ACL reconstruction, were randomly assigned at their 6-month follow-up visit into two groups: 15 participants in each group (resistance or plyometric training group). Each group underwent two training sessions weekly for 8 weeks. The participants were assessed at baseline and after completed the training period for the single leg 6-meter timed hop, knee joint position sense, static and dynamic balance, isokinetic muscle strength and the International Knee Documentation Committee Subjective Knee Form.

Results: Post an 8-week training period, both groups showed improvements in the single leg 6-meter timed hop. Notably, the limb symmetry index for this hop in the plyometric group was significantly higher than the resistance group {18.2% (10.2, 26.1) vs 6.2% (-2.0, 14.5) respectively}. The plyometric group also demonstrated significantly better knee joint position sense {-3.1° (-4.3, -1.9) vs -0.8° (-2.0, 0.4) respectively}and the unipedal stance on a stable surface with eyes closed {13.9 sec (2.7, 25.2) vs -2.6 sec (-14.3, 9.1) respectively} than the resistance group.

Conclusion: Plyometric training in the late phase of ACL rehabilitation program has proven to be a suitable and effective approach for enhancing neuromuscular and knee functions.

Keywords: Anterior cruciate ligament reconstruction; plyometric; neuromuscular functions (Siriraj Med J 2024; 76: 353-365)

INTRODUCTION

The anterior cruciate ligament (ACL) is one of the most injured in sports, especially those that involve rapid movement, jumping or landing.[1,2] Patients following an ACL injury encountered several knee functions deficit and knee laxity.[1] Arthroscopic ACL reconstruction is a common procedure to restore knee stability following an ACL injury.[2,3] Post-reconstruction, many patients struggle with muscle strength and neuromuscular deficits, contributing to difficulties in returning to sports and an increased risk of re-injury.[4-8]

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Rehabilitation is crucial for recovery after ACL reconstruction, and is typically divided into early, intermediate and late phases.[3] While early and intermediate phases have been well-studied such as accelerated rehabilitation or using blood flow restriction training, data on late phase rehabilitation is limited.[4,9,10] Late phase training programs after ACL reconstruction focus on enhancing muscle strength and neuromuscular functions to support increased physical activity.[10,11] Although resistance training has been a traditional method for improving muscle strength,[5] it may not effectively improve lower limb power and proprioception, which are vital neuromuscular functions for returning to sports after ACL reconstruction.[11,12] In addition,

The plyometric training program, consisting of jumping and landing movements, incorporates a stretch-shortening cycle (SSC).[13] This type of training has been used to improve neuromuscular function.[14] Literature reviews reveal studies reporting positive effects of plyometric training following ACL reconstruction.[15-18] However, there is a scarcity of randomized controlled trial focusing on plyometric training.[17,18] Therefore, this study aimed to determine the effects of plyometric training programs on neuromuscular and knee functions during the late phase of rehabilitation after ACL reconstruction. The hypothesis is that plyometric training may lead to significant improvements in neuromuscular and knee functions compared to resistance training.

MATERIALS AND METHODS

Study Design and Setting

This randomized controlled trial was conducted from April 2022 to March 2023 at Faculty of Medicine Siriraj Hospital, Mahidol University, Bangkok, Thailand. The approval of the study protocol from the institutional review board (COA no. Si 264/2022) and was registered with the Clinical Trails Registry (TCTR20220608003).

Participants

This study enrolled patients who had follow-up at their 6-8 months after undergoing unilateral ACL reconstruction using both of difference autografts: bone-patellar tendon-bone or hamstring tendon autografts. Recruitment occurred at Siriraj Hospital during clinical follow-ups. Eligible participants were aged 18 to 45 years at enrollment. To qualify for the study, subjects needed to demonstrate passive knee extension within 3° of the nonsurgical side, passive knee flexion within 5° of the unaffected side, a pain rating scale of less than 2 out of 10 during daily activities, and a limb symmetry index of isokinetic muscle strength exceeding 60% of the nonsurgical side. Patients with a history of fractures or dislocations in the lower extremities, multi-ligament knee injuries, inflammatory joint diseases, and cognitive neuromuscular impairments were excluded. Additionally, a less than 80% compliance (attending fewer than 13 out of 16 (80%) training sessions) was also reason for exclusion from the study. Assessments were conducted at baseline and after completing an 8-week training program. Measurements included the International Knee Documentation Committee Subjective Knee Form (IKDC-SKF), static and dynamic balance, knee joint position sense, isokinetic muscle strength and single leg 6-meter timed hop test. All functional tests were assessed by highly skilled sports scientist at Siriraj Hospital. All patients provided written consent before participating in this study.

Randomization and Interventions

All participants were operated on at Siriraj Hospital by the same surgeon and underwent ACL reconstruction using either autografts. Following surgery, they participated in a standard rehabilitation protocol, starting with the early phase of rehabilitation overseen by highly skilled sports scientists until enrollment in the study. At their 6-8 months follow-up visit, eligible patients were randomly assigned into two groups through a computer-generated block of four: the resistance training group or the plyometric training group. After baseline testing, participants of both groups received instruction and supervision for their respective exercise training programs from highly skilled sports scientist of Division of Sports Medicine, Department of Orthopaedic Surgery, Siriraj Hospital, and under the guidance of Dr. Napasakorn Chuensiri who holds the Certified Strength and Conditioning Specialist (CSCS). The participants were asked to perform maximum or explosive movement in all exercise. Moreover, sports scientists provided effective feedback to participants of their training. In addition, the participants did not receive a home exercise program. The training regimen for both groups involved two sessions per week over an eight-week period, with each session comprising a, 10-minute for dynamic warm up, 40-minute exercise protocol, and 10-minute for cool down.

Resistance training protocol

Participants were instructed to exercise following a resistance training protocol based on based on the American College of Sports Medicine's guidelines.[18] This protocol involved exercises at 75% of their 1-repetition maximum (RM), consisting of 3 sets of 10 repetitions each, with a minute's rest between sets. The program

included four exercises: squats, side lunges, step ups, and heel raises. Participants used dumbbells as external loads during these exercises. The intensity, set at 75% of their 1RM, was calculated both at the baseline and after four weeks of the training period.

Plyometric training protocol

The plyometric protocol was designed with an intensity of 80-100 foot contacts per training session, in line with recommendations by *Buckthorpe et al.*[20] This protocol included four exercises, each performed in four sets with five repetitions, and a two-minute rest between sets. The 8-week training protocol was split into two phases. The first phase of the plyometric training program compromised four exercises: squat jumps, ankle hops, step-up jumps, and lateral bound stick landings. After the initial 4 weeks, the patients moved to the second phase, which included squat jumps to a box, ankle jumps, step-up alternate jumps, and lateral bounds. All exercises were performed using bodyweight.

Outcome Measures

The patient-reported outcome measure was assessed using the Thai version of the IKDC-SKF. This 18-item questionnaire assess knee symptoms, functions and sports activities, with scores ranging from 0 to 100.[21] Higher scores indicate better knee function. Test-retest reliability was excellent (ICC = 0.92).[21]

The unipedal stance test, used to assess static balance, involved four positions; standing on one leg on a stable surface with eyes open, the same with eyes closed, standing on one leg on an unstable surface which used foam balance pad cushion thickened with smooth surface (39 cm x 24 cm x 6 cm) with eyes open, and finally, the same with eyes closed. Participants were asked to stand on one leg with their arms crossed over their chest. The duration for which they could maintain each position without uncrossing their arms, moving their foot from the starting position, rotating their foot on the ground, opening their eyes during the closed-eye trials, or reaching a maximum of 45 seconds, was timed using a stopwatch.[22] Each position was attempted three times on both legs, starting with the unaffected knee, followed by the affected side, and the best time of each trial was recorded in seconds.

Dynamic balance was assessed using the modified star excursion balance test (mSEBT).[23] Participants were instructed to stand on one leg at a central point on the floor, with three reach lines arranged in a 'Y' shape, labeled anterior, posteromedial and posterolateral. They were instructed to reach as far as possible along each line with a light touch, and then return the reaching leg to the center. The test was repeated three times for both legs, starting with the unaffected knee, followed by the affected side, recording the best reach distance in centimeters for each direction.

Knee joint position sense, an indicator of knee proprioception, was assessed using an isokinetic dynamometer (CONTREX MJ multijoint module 2018, Physiomed, Germany).[23] The seat was set with their hip and knee flexed at 90°. With their eyes closed, their knee was initially flexed to 90° and then passively moved to 45° of knee flexion. Participants were asked to remember this target position for 5 seconds before returning to the starting position. Then, the knee was passively moved again, and participants pressed a button when they believed their knee reached the previous target angle. The difference in knee angles was recorded. Each leg was tested twice, starting with the unaffected knee, followed by the affected side. The consistency of the test showed good test-retest reliability (ICC=0.78).[24]

Muscle strength was assessed using an isokinetic dynamometer to measure peak extensor and flexor torque of the knee.[24] Prior to isokinetic muscle strength testing, participants warmed up for 5 minutes on a stationary bicycle at 60-70 revolutions per minute without resistance. After warming up, they were instructed to seated with an isokinetic dynamometer attached to their hip and knee flexed 90°. A shoulder pad across the chest and a seat strap on the middle of the thigh helped minimize body movement during the test. Participants first performed 15 repetitions at an angular velocity of 180°/sec as an additional warm-up, followed by three repetitions of maximum effort tests at an angular velocity of 60°/sec, with a 30-second rest period in between. The testing was conducted twice on each leg, starting with the unaffected knee and then the affected side. The best time for each leg was also recorded.

Hopping time was evaluated using the single leg 6-meter timed hop test.[25] Participants began by standing on a single leg at the starting position and then hopped as quickly as possible over a distance of 6 meters, with the timer stopping as they crossed the finish line. Each participant performed this test twice on both legs, starting with the unaffected knee, followed by the affected side.[25] The single leg 6-meter timed hop test demonstrated good test-retest reliability in patients in this patients group (ICC = 0.82).[26]

Sample Size and Statistical Analysis

The sample size calculation for this study was performed using G*power software version 3.1.9.2, focusing on

the primary outcome of knee proprioception, based on results from a previous study.[17] In that study the mean in the experimental group was 4.3 and 6.7 in the control group. The standard deviation was 2.4. The type I error was set at 0.05, the power at 80% and the effect size at 0.5, resulting in a sample size of 13 in both groups.

Descriptive statistics were analyzed to compile participant characteristics. Data was checked for a normal distribution using Shapiro-Wilk test. The test revealed no significant deviation from a normal distribution. For categorical data, frequencies and percentages were used, while the means and standard deviations were reported for continuous data. To assess differences between groups, Chi-squared tests were applied for categorical data, and independent t-tests were used for continuous data.

The analysis of outcome measures was conducted using mixed model ANOVA. This was followed by LSD post-hoc comparisons to determine significant differences between the groups. Statistical analysis was performed using PASW software for Windows version 18. P-values of less than 0.05 were considered statistically significant.

RESULTS

As illustrated in Fig 1, 30 patients successfully participated in this study and were randomly allocated during their 6-8 months follow-up visit into two groups.

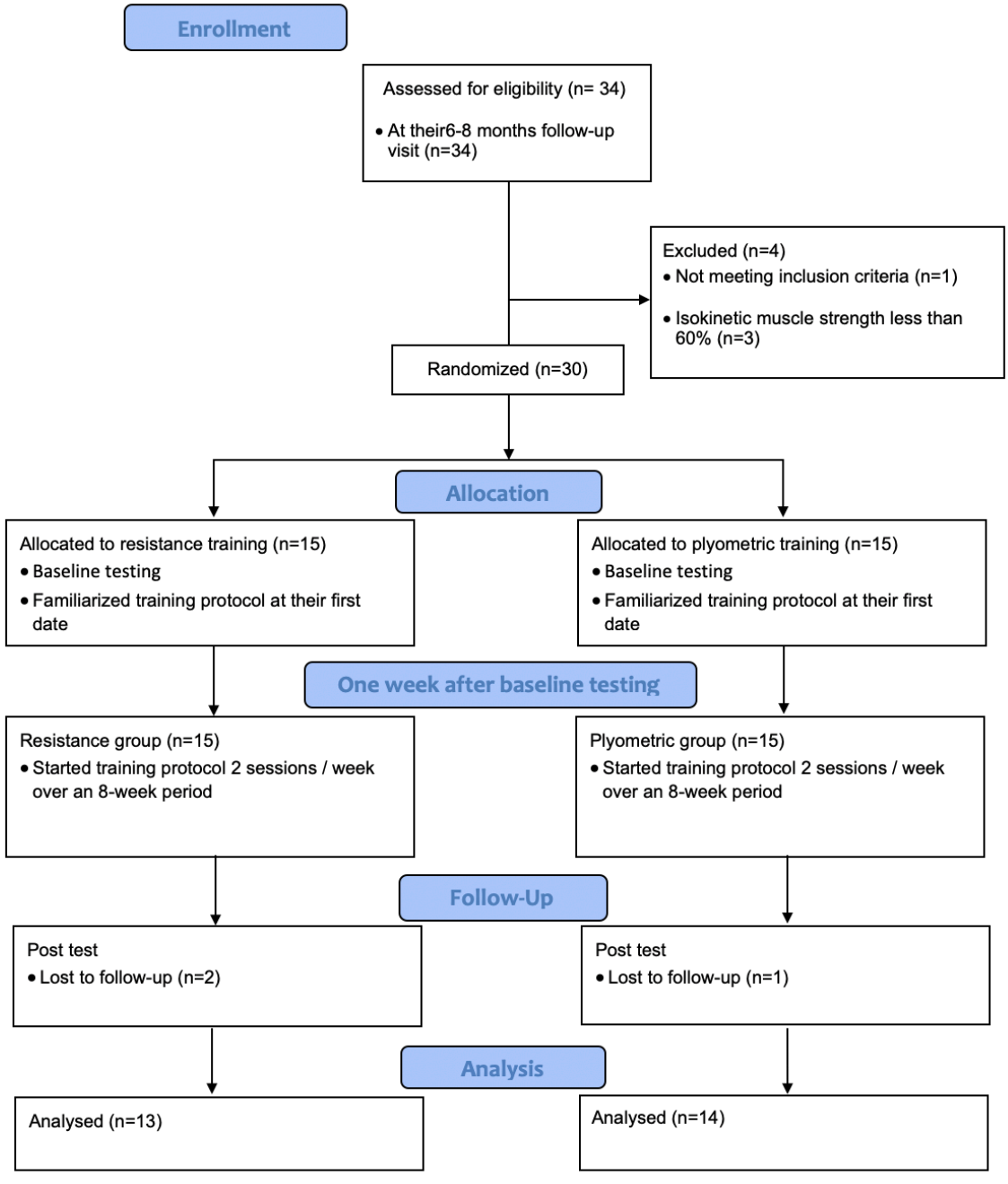


Fig 1. CONSORT flow chart of study enrollment

After completed baseline testing, each participant was familiarized with their training protocol from the first date of their enrollment in this study. After one week, participants started their training protocol, and received one-on-one training sessions with highly skilled sports scientist. Participants underwent a total of 16 training sessions over an 8-week period, compliance with the 16 training sessions was closely monitored. Three participants who were lost to follow-up dropped out of this study. The remaining twenty-seven participants, who attended more than 13 out of 16 (80%) training sessions and reported no serious adverse events, pain or accidents that exceeded the indicated threshold, were included in the analysis.

The characteristics of the participants, categorized into groups is presented in Table 1. There were no significant differences in the characteristics of patients between the two groups. The study group compromised 27 participants as the mean time elapsed from surgery to study enrollment was 6 months. All participants were classified as engaging in recreational activity levels. Baseline measurements of isokinetic muscle strength revealed no significant differences between the groups.

In the plyometric group, the single leg 6-meter timed hop improved significantly (p=0.041) more, -1.1 sec (95% CI; -1.6, -0.7) than in the resistance group, -0.5 sec (95% CI: -1.0, -0.1). In the plyometric group, the LSI percentage improved significantly (p=0.041) more, 18.2% (10.2, 26.1), than in the resistance group, 6.2% (95%CI: -2.0, 14.5). (Fig 2)

The plyometric group demonstrated significantly improved in the knee joint position sense for the affected (p=0.009) more, -3.1° (95% CI; -4.3, -1.9) than in the resistance group, -0.8° (95% CI; -2.0, 0.4). The unaffected of the plyometric group also showed significantly improved (p=0.015) more, -1.3° (95% CI; -2.1, -0.5) than in the resistance group, 0.1° (95% CI -0.7, 0.9) (Fig 3)

The plyometric group's unipedal stance test, one leg stance on a stable surface with closed eyes for the affected leg improved significantly (p=0.045) more, 13.9 sec (95% CI; 2.7, 25.2) than in the resistance group, -2.6 sec (95% CI; -14.3, 9.1). (Table 2) Dynamic balance using the mSEBT, the plyometric group showed a tendency to improve in anterior direction, the posterolateral direction and composite scores for affected leg more effectively compared to the resistance group. (Table 2)

There were no significant changes in either group regarding isokinetic muscle strength in knee extension and flexion (Table 3).

The IKDC-SKF did not change significantly in the resistance and plyometric groups {5.5% (-3.0, 13.9) and 6.6% (-1.6, 14.8) respectively}.

DISCUSSION

This study compared resistance and plyometric training programs regarding effects on neuromuscular and knee functions during the late phase of rehabilitation following ACL reconstruction, which occurred 6-8 months post-operation. The key finding of this study is that improvements in the LSI of this hop were significant only in the plyometric group, and improved significantly greater than the resistance group. In addition, the plyometric group also showed significant greater in knee joint position sense of both legs and static balance on a stable surface with closed eyes for the affected leg than the resistance group. While the late phase ACL rehabilitation program traditionally uses resistance training for optimizing neuromuscular response to strength training, this study indicates that, plyometric training, known for inducing specific neural patterns through SCCs, could be a superior method for enhancing functional performance. These findings confirm the positive effects of plyometric training in late phase rehabilitation post-ACL reconstruction.

In this study, the single leg 6-meter timed hop (6MTH) served as a measure of functional performance and lower limb power. Both the resistance and training groups showed significant improvements in 6MTH, indicating enhanced lower limb power. This improvement is attributed to increased motor unit recruitment, stimulating fast-twitch fibers and growth hormone secretion[34], which are crucial for muscle activation enhancement. However, the plyometric group exhibited greater improvement in 6MTH. Plyometric training including unilateral and bilateral jumping which is ascribed to the SSCs inherent in plyometric training, where the eccentric phase stretches muscle spindles, and increasing afferent nerve firing. The rate of muscle spindle stretch dictates the signal intensity sent to the spinal cord, with faster stretches leading to greater motor recruitment.[12,32] Additionally, the LSI in the plyometric group was 91% when comparing the operated leg to the normal leg, which is significantly higher than that in the resistance group. This LSI level, surpassing 90% cutoff, is a critical factor in deciding whether to return to sports activities post ACL reconstruction.[27] These findings showed that plyometric training can positively influence decisions regarding clearance to return to sports after ACL reconstruction.

Knee joint position sense is the important factor to improve the LSI. Our study demonstrated that knee joint position sense in both legs improved significantly after an 8-week plyometric training program, more so than with resistance training. Plyometric training is crucial for enhancing knee joint position sense.[14] Plyometric training consists of jumping and landing, which continuously stimulates mechanoreceptors, Golgi tendon organs, and

TABLE 1. Physiological characteristics and anthropometry variables in patients post-ACL reconstruction before and after 8 weeks training in the resistance and plyometric groups (n=27)

Characteristics	All data (n=27)	Resistance (n = 13)	Plyometric (n = 14)	p-value
Gender				
Male	24 (88.9%)	12 (92.3%)	12 (85.7%)	0.586
Female	3 (11.1%)	1 (7.73%)	2 (14.3%)	
Age (years)	29.0 ± 7.2	28.2 ± 6.8	29.8 ± 7.7	0.583
Weight (kg)	72.9 ± 9.6	70.9 ± 10.3	74.6 ± 8.9	0.325
Height (cm)	171.9 ± 6.2	172.3 ± 6.4	171.4 ± 6.0	0.719
Body mass index (kg/m^2)	24.6 ± 2.7	23.8 ± 2.9	25.4 ± 2.5	0.149
Side of affected knee				
Right	13 (48.1%)	6 (46.2%)	7 (50.0%)	0.842
Left	14 (51.9%)	7 (53.8%)	7 (50.0%)	
Follow up period (months)	6.2 ± 0.4	6.2 ± 0.4	6.2 ± 0.4	0.922
Tegner activities scale				
5	2 (7.4%)	1 (7.7%)	1 (7.1%)	
6	2 (7.4%)	0 (0%)	2 (14.3%)	0.366
7	23 (85.2%)	12 (92.3%)	11 (78.6%)	
Sports type				
Football	20 (71.4%)	10 (71.4%)	10 (71.4%)	
Basketball	2 (7.1%)	1 (7.1%)	1 (7.1%)	0.504
Badminton	2 (7.1%)	0 (0%)	2 (14.3%)	
Other	3 (10.7%)	2 (14.3%)	1 (7.1%)	
Graft type				
BPTB	8 (29.6%)	4 (28.6%)	4 (28.6%)	0.901
HS	19 (70.4%)	9 (69.2%)	10 (71.4%)	
Combined procedure				
No	13 (46.4%)	5 (35.7%)	8 (57.1%)	
Meniscectomy	10 (35.7%)	6 (42.9%)	4 (28.6%)	0.524
Meniscus repair	5 (17.9%)	3 (21.4%)	2 (14.3%)	
Extension peak torque				
Affected (Nm)	147.9 ± 44.0	148.8 ± 40.8	147.1 ± 48.3	0.927
Unaffected (Nm)	183.3 ± 47.7	182.6 ± 42.1	184.0 ± 54.1	0.942
LSI (%)	80.3 ± 9.9	80.9 ± 8.8	79.8 ± 11.2	0.764

Abbreviations: BPTB - bone patellar tendon bone; HS - hamstring; LSI - limb symmetry index

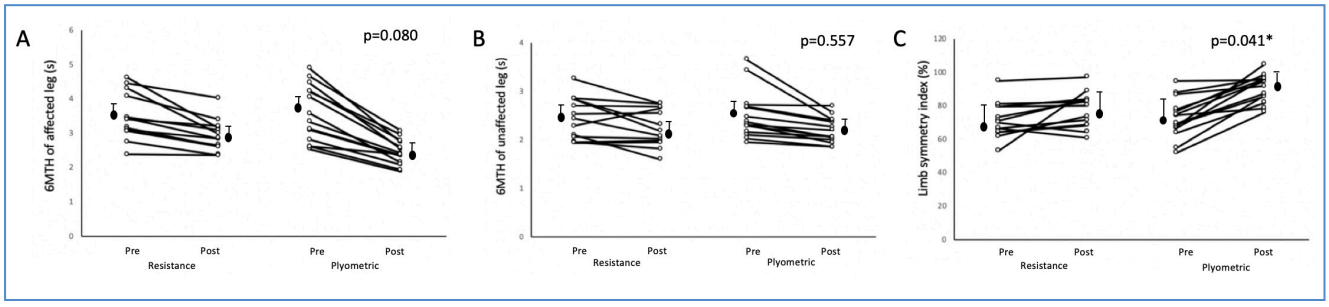


Fig 2. Scatterplots demonstrating paired data of individual changes in single leg 6-meter timed hop in affected (A), unaffected (B), and limb symmetry index (C) in response to the resistance group (n=13) and the plyometric group (n=14). *The statistic significantly difference of the Time * Group interactions ($p < 0.05$).

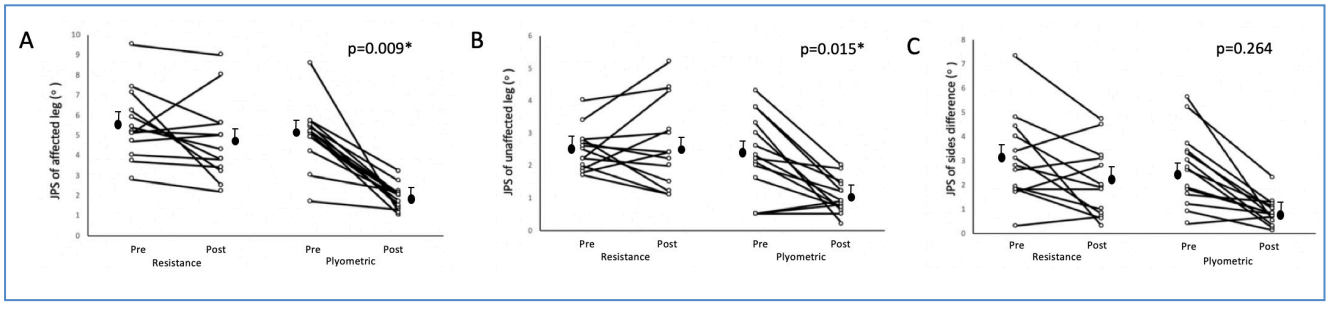


Fig 3. Scatterplots demonstrating paired data of individual changes in joint position sense in affected (A), unaffected (B), and limb symmetry index (C) in response to the resistance (n=13) and plyometric group (n=14). *The statistic significantly difference of the Time * Group interactions ($p < 0.05$).

muscle spindles around the knee joint. This repetitive stimulation increases the sensitivity of sensory responses and the perception of knee joint.[14,28] Previous studies corroborate these findings, showing that athletes with post-ACL reconstruction experienced improved knee joint position sense following neuromuscular training programs that included jumping exercises[17] Similarly, female athletes showed improved knee proprioception after a 6-week plyometric training period.[29] In addition, improvements in the Golgi tendon organ positively affect the reduction of force on the knee joint.[28] These findings found that such training plays a vital role in developing knee proprioception, which is crucial for returning to sports and reducing the risk of re-injury after ACL reconstruction.

Moreover, balance is a major factor that affects functional mobility in patients post-ACL reconstruction,[30,31] which is often impaired due to neuromuscular damage from injury and subsequent reconstruction. In this study improvements in static balance, measured by the unipedal stance test, were significantly larger in the plyometric group compared to the resistance group. Plyometric training played a crucial role in improving balance, primarily by repeatedly stimulating the afferent sensory pathways during the plyometric training period.[18] In addition, when visual input is removed, the nervous system must rely on increases reliance on proprioceptive feedback from joints and muscles to maintain balance.[30] Its indicated that the plyometric group demonstrated greater improvement in proprioceptive feedback than resistance training group. Furthermore, the dynamic balance of the mSEBT indicate that the plyometric group tended to show greater improvement in the anterior, posterolateral direction and composite scores for affected leg more effectively compared to the resistance group. These results are attributable to mSEBT's reliance on feed-forward control and visual feedback until toe touch, triggered by knee joint perception.[30] This feedback provides information about limb position, movement, and spatial orientation, crucial for maintaining balance.[32] Plyometric training has been shown to enhance the sensitivity of the afferent feedback pathway.[32] Moreover, the percentage change of composite score summaries of this study were greater than the minimal detectable change (10.4 vs 7.2 respectively).[33] These findings support the beneficial effects of incorporating plyometric exercises into rehabilitation programs for individuals recovering to improve balance.

In this study, peak isokinetic torque of the knee appeared to improve under both training protocols. However, no statistically significant difference was observed from the baseline, nor was there a notable difference between the groups. This lack of significant improvement could be attributed to participants already having undergone resistance protocol training in the early

TABLE 2. Static and dynamic balance in patients after ACL reconstruction before and after 8 weeks training in the resistance and plyometric group.

Variables	Resistance group (n=13)			Plyometric group (n=14)			ANOVA statistic			Effect size	T-test p value
	Baseline (mean ± SD) (95% CI)	Post-test (mean ± SD) (95% CI)	Δ change (95%CI)	Baseline (mean ± SD) (95% CI)	Post-test (mean ± SD) (95% CI)	Δ change (95%CI)	Time	Group	Time*Group		
Unipedal stance											
SOE											
Affected (sec)	40.4 ± 8.8 (37.3, 43.5)	42.7 ± 5.7 (39.6, 45.8)	2.3 (-2.1, 6.6)	43.7 ± 4.0 (40.7, 46.7)	44.8 ± 0.8 (41.8, 47.8)	1.1 (-3.1, 5.3)	0.276	0.080	0.693	0.003	0.718
Unaffected (sec)	41.9 ± 7.2 (39.5, 44.4)	44.0 ± 3.4 (41.6, 46.5)	2.1 (-1.4, 5.6)	43.9 ± 4.0 (41.6, 46.3)	45.0 ± 0.0 (42.6, 47.4)	1.1 (-2.3, 4.4)	0.190	0.224	0.665	0.004	0.688
SCE											
Affected (sec)	18.2 ± 16.9 (9.9, 26.4)	15.6 ± 12.7 (7.3, 23.8)	-2.6 (-14.3, 9.1)	13.0 ± 13.6 (5.1, 21.0)	26.9 ± 15.7* (19.0, 34.9)	13.9† (2.7, 25.2)	0.168	0.446	0.045	0.078	0.012
Unaffected (sec)	21.0± 15.8 (12.3, 29.7)	21.9 ± 14.2 (13.2, 30.6)	0.9 (-11.4, 13.2)	17.7 ± 15.7 (9.2, 26.0)	28.0 ± 16.5 (19.5, 36.2)	10.2 (-1.6, 22.1)	0.198	0.764	0.279	0.023	0.073
UOE											
Affected (sec)	31.3 ± 17.1 (18.6, 35.8)	27.2 ± 15.9 (22.7, 39.9)	4.1 (-8.1, 16.2)	24.5 ± 17.4 (16.2, 32.7)	39.6 ± 10.6 31.3, 47.9)	15.1 (3.4, 26.9)	0.027	0.515	0.195	0.033	0.079
Unaffected (sec)	33.1 ± 13.4 (26.5, 39.7)	33.0 ± 13.8 (26.4, 39.7)	-0.1 (-9.4, 9.3)	31.3 ± 12.4 (24.9, 37.7)	41.9 ± 7.2 (35.5, 48.3)	10.6† (1.6, 19.6)	0.109	0.280	0.105	0.052	0.033
UCE											
Affected (sec)	3.1 ± 1.7 (1.1, 5.0)	4.9 ± 3.6 (3.0, 6.8)	1.9 (-0.8, 4.6)	2.8 ± 1.3 (1.0, 4.7)	6.2 ± 5.3 (4.4, 8.0)	3.4 (0.8, 6.0)	0.007	0.573	0.418	0.013	0.318
Unaffected (sec)	4.8 ± 4.0 (2.3, 7.3)	5.9 ± 5.3 (3.4, 8.4)	1.1 (-2.5, 4.6)	3.9 ± 1.7 (1.4, 6.3)	7.0 ± 5.9 (4.6, 9.4)	3.1 (-0.3, 6.5)	0.093	0.941	0.414	0.013	0.209

TABLE 2. Static and dynamic balance in patients after ACL reconstruction before and after 8 weeks training in the resistance and plyometric group. (Continue)

Variables	Resistance group (n=13)			Plyometric group (n=14)			ANOVA statistic			Effect size	T-test p value
	Baseline (mean ± SD) (95% CI)	Post-test (mean ± SD) (95% CI)	Δ change (95%CI)	Baseline (mean ± SD) (95% CI)	Post-test (mean ± SD) (95% CI)	Δ change (95%CI)	Time	Group	Time*Group		
The modified star excursion balance											
ANT											
Affected (cm)	56.0 ± 5.8 (52.5, 59.5)	59.0 ± 5.2 (55.5, 63.0)	3.0 (-1.9, 7.9)	55.9 ± 6.0 (52.6, 59.3)	63.1 ± 7.5 (59.8, 66.5)	7.2† (2.5, 11.9)	0.004	0.234	0.218	0.030	0.005
Unaffected (cm)	60.1 ± 6.4 (56.3, 63.7)	62.9 ± 6.3 (58.9, 66.3)	2.8 (-2.1, 7.6)	50.9 ± 4.7 (56.7, 64.1)	64.7 ± 7.0 (60.9, 68.4)	4.9 (0.2, 9.5)	0.027	0.625	0.537	0.008	0.267
PM											
Affected (cm)	75.9 ± 8.1 (71.6, 80.3)	80.0 ± 8.8 (75.7, 84.3)	4.1 (-2.1, 10.2)	75.1 ± 7.4 (70.8, 79.3)	80.7 ± 6.9 (76.5, 84.9)	5.6 (-0.3, 11.6)	0.026	0.974	0.714	0.003	0.529
Unaffected (cm)	79.9 ± 7.4 (75.6, 84.3)	82.1 ± 9.3 (77.8, 86.4)	2.2 (-4.0, 8.3)	77.7 ± 7.3 (73.5, 81.9)	81.6 ± 6.9 (77.7, 86.4)	3.9 (-2.0, 9.6)	0.162	0.524	0.689	0.003	0.517
PL											
Affected (cm)	69.8 ± 10.6 (64.7, 74.8)	74.8 ± 8.9 (69.7, 79.8)	5.0 (-2.1, 12.1)	67.9 ± 7.6 (63.0, 72.7)	78.1 ± 8.8 (73.3, 83.0)	10.3† (3.4, 17.1)	0.003	0.768	0.288	0.023	0.044
Unaffected (cm)	74.9 ± 9.2 (70.0, 79.7)	78.1 ± 9.3 (73.2, 82.9)	3.2 (-3.6, 10.1)	70.8 ± 5.7 (66.1, 75.5)	80.4 ± 10.0 (75.7, 85.0)	9.6 (3.0, 16.2)	0.009	0.709	0.187	0.035	0.050
Composite											
Affected (%)	78.7 ± 6.8 (75.8, 82.7)	83.5 ± 6.6* (80.2, 87.2)	4.8 (0.1, 9.4)	77.9 ± 4.7 (74.7, 81.1)	87.0 ± 5.6 (83.2, 90.1)	9.1† (4.6, 13.6)	<0.001	0.401	0.189	0.034	0.028
Unaffected (%)	83.9 ± 6.1 (80.6, 87.2)	87.1 ± 7.3 (83.9, 90.4)	3.2 (-1.4, 7.9)	81.7 ± 3.9 (78.6, 84.9)	88.9 ± 5.9 (83.8, 90.4)	7.1 (2.7, 11.6)	0.002	0.899	0.228	0.029	0.072

Abbreviations: SOE - Stable with opened eyes; SCE - Stable with closed eyes; UOE - Unstable with opened eyes; UCE - Unstable with closed eyes; ANT - anterior; PM - posteromedial; PL - posterolateral; 95%CI - 95% confidence interval

*The statistic significantly difference of the Time * Group interactions ($p < 0.05$).

†The difference change between group in independent t test were statistically significant ($p < 0.05$)

TABLE 3. Isokinetic muscle strength in patients post-ACL reconstruction before and after 8 weeks training in the resistance and plyometric group.

Variables	Resistance group (n=13)			Plyometric group (n=14)			ANOVA statistic			Effect size	T-test p value
	Baseline (mean ± SD) (95% CI)	Post-test (mean ± SD) (95% CI)	Δ change (95%CI)	Baseline (mean ± SD) (95% CI)	Post-test (mean ± SD) (95% CI)	Δ change (95%CI)	Time	Group	Time*Group		
Peak torque of extension											
Affected (Nm)	148.8 ± 40.8 (122.4, 175.1)	159.0 ± 43.4 (132.7, 185.4)	10.3 (-27.0, 47.5)	147.2 ± 48.3 (121.8, 172.5)	165.5 ± 54.6 (140.1, 190.8)	18.3 (-17.6, 54.2)	0.272	0.852	0.757	0.002	0.313
Unaffected (Nm)	182.6 ± 42.1 (153.2, 212.1)	201.8 ± 53.1 (172.3, 231.2)	19.3 (-22.5, 60.8)	184.0 ± 54.1 (155.6, 212.4)	196.7 ± 59.8 (168.4, 225.1)	12.7 (-27.4, 52.8)	0.274	0.899	0.825	0.001	0.372
LSI (%)	81.0 ± 8.8 (74.3, 87.6)	82.4 ± 16.4 (75.7, 89.1)	1.4 (-8.0, 10.9)	79.8 ± 11.2 (73.3, 86.2)	83.8 ± 10.4 (77.4, 90.3)	4.1 (-5.1, 13.2)	0.405	0.967	0.690	0.003	0.510
Torque average @ 0.2 second of extension											
Affected (Nm)	137.7 ± 46.5 (114.8, 160.6)	131.0 ± 41.4 (108.1, 153.9)	-6.7 (-39.1, 26.7)	114.9 ± 37.8 (92.8, 137.0)	119.1 ± 38.7 (97.1, 141.2)	4.2 (-27.0, 35.4)	0.913	0.128	0.629	0.005	0.171
Unaffected (Nm)	159.8 ± 54.1 (132.7, 186.9)	169.8 ± 47.6 (142.7, 196.9)	10.0 (-28.3, 48.3)	142.6 ± 50.4 (116.5, 168.8)	143.5 ± 42.2 (117.4, 169.2)	0.9 (-36.1, 37.8)	0.684	0.107	0.732	0.002	0.108
Peak power of extension											
Affected (W)	153.7 ± 44.7 (125.8, 181.6)	166.9 ± 45.7 (139.0, 194.8)	13.2 (-26.2, 52.6)	154.6 ± 50.8 (127.8, 181.5)	174.5 ± 57.4 (147.6, 201.4)	19.9 (-18.1, 57.9)	0.231	0.756	0.808	0.001	0.416
Unaffected (W)	190.0 ± 46.2 (159.0, 221.0)	211.6 ± 55.6 (180.5, 242.6)	21.6 (-22.3, 65.4)	193.2 ± 56.6 (163.3, 223.1)	207.0 ± 62.4 (180.5, 242.6)	13.8 (-28.5, 56.0)	0.249	0.963	0.799	0.001	0.118
Peak torque of flexion											
Affected (Nm)	103.7 ± 27.0 (85.0, 122.5)	111.6 ± 28.0 (92.8, 130.3)	7.8 (-18.7, 34.4)	98.2 ± 36.6 (80.1, 116.2)	110.3 ± 40.3 (92.2, 128.4)	12.1 (-13.5, 37.7)	0.282	0.710	0.817	0.001	0.363
Unaffected (Nm)	109.7 ± 30.6 (91.2, 128.1)	122.3 ± 33.3 (103.9, 140.7)	12.6 (-13.4, 38.7)	107.4 ± 32.2 (89.7, 125.2)	112.8 ± 35.8 (95.1, 130.6)	5.4 (-19.7, 30.5)	0.322	0.518	0.690	0.003	0.169
LSI (%)	95.9 ± 13.3 (87.7, 104.0)	95.3 ± 15.2 (87.1, 103.5)	-0.5 (-12.0, 11.0)	90.7 ± 15.7 (82.8, 98.6)	95.1 ± 14.0 (87.3, 103.0)	4.4 (-6.7, 15.5)	0.626	0.505	0.537	0.008	0.364

TABLE 3. Isokinetic muscle strength in patients post-ACL reconstruction before and after 8 weeks training in the resistance and plyometric group. (Continue)

Variables	Resistance group (n=13)			Plyometric group (n=14)			ANOVA statistic			Effect size	T-test p value
	Baseline (mean ± SD) (95% CI)	Post-test (mean ± SD) (95% CI)	Δ change (95%CI)	Baseline (mean ± SD) (95% CI)	Post-test (mean ± SD) (95% CI)	Δ change (95%CI)	Time	Group	Time*Group		
Torque average @ 0.2 second of flexion											
Affected (Nm)	97.6 ± 41.4 (78.2, 117.0)	102.0 ± 28.8 (82.6, 121.4)	4.4 (-23.0, 31.9)	86.9 ± 37.7 (68.1, 105.6)	91.6 ± 29.8 (72.9, 110.3)	4.7 (-21.7, 31.2)	0.633	0.270	0.988	0.001	0.989
Unaffected (Nm)	101.7 ± 36.3 (82.2, 121.3)	112.7 ± 32.9 (93.1, 132.3)	10.9 (-16.7, 38.6)	90.8 ± 37.4 (71.9, 109.6)	92.6 ± 33.6 (73.7, 111.4)	1.8 (-24.9, 28.4)	0.509	0.110	0.634	0.005	0.194
Peak power of flexion											
Affected (W)	108.7 ± 26.7 (89.7, 127.7)	115.1 ± 27.8 (96.1, 134.1)	6.4 (-20.4, 33.3)	103.3 ± 37.0 (83.0, 119.6)	111.3 ± 41.7 (96.1, 134.1)	9.9 (-16.0, 35.8)	0.384	0.552	0.851	0.001	0.929
Unaffected (W)	114.2 ± 29.9 (95.7, 132.7)	125.8 ± 2332.7 (107.3, 144.2)	11.6 (-14.5, 37.7)	110.5 ± 33.4 (92.7, 128.3)	117.0 ± 36.0 (99.2, 134.8)	6.5 (-18.7, 31.6)	0.322	0.495	0.777	0.002	0.156

Abbreviations: LSI - limb symmetry index; 95%CI - 95% confidence interval

phase of rehabilitation prior to this study. Additionally, the IKDC-SKF showed no statistically significant changes after the 8-week training period. However, the mean score of IKDC-SKF for the resistance and plyometric groups were 81% and 88% respectively, indicating a high level of knee function in daily or sport activities.[14]

In addition, while previous research often focused on plyometric training in competitive athletes,[16-18, 29] this study highlights its benefits for recreational athletes. Importantly, all participants were able to perform the training without any adverse effects following one-one training sessions. However, our study has some limitations. First, it mostly recruited male patients which may limit the generalizability of the findings to female populations. Second, requiring all participants to have quadriceps muscle strength greater than 60% of the unaffected leg which crucial in ensuring a baseline level of strength. Therefore, the participant had received an adequate muscle strength training program before participating in this study. Last, all participants were in a recreational athlete which may had a good skill for plyometric training. Future studies could explore the efficacy of this protocol in non-athletes.

CONCLUSION

The late phase rehabilitation program, incorporating plyometric training has proven to be effective in improving neuromuscular and knee functions greater than the conventional resistance training in ACL reconstruction patients. This supervised training program can be safely executed without any adverse effects, making it suitable even for recreational level athletes.

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Author contributions

Wacharapol and Napasakorn were developed the theory and designed the experimental in consultation with Pisit. All authors were involved in data collection and contributed to the interpretation of the results. Wacharapol and Napasakorn took the lead in drafted and prepared the manuscript. All authors provided critical feedback and approved the final version of the manuscript.

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