

# Effects of Eccentric Training and Functional Resistance Training to Improve Muscle Strength and Functional Performance After Anterior Cruciate Ligament Reconstruction

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## ABSTRACT

### BACKGROUND OF THE STUDY

Anterior Cruciate Ligament (ACL) injuries are among the most common knee injuries, particularly in athletes participating in high-impact sports. ACL reconstruction is often required to restore knee stability and function; however, post-surgical rehabilitation plays a crucial role in achieving optimal recovery. Eccentric training, which involves lengthening muscle contractions under load, has been shown to enhance muscle hypertrophy, strength, and tendon properties, making it a crucial component in ACL rehabilitation. On the other hand, functional resistance training, which mimics sport-specific and daily movement patterns, aims to restore neuromuscular coordination and improve dynamic stability. While both training methods have been used in rehabilitation, their combined effects on muscle strength and functional performance post-ACLR remain an area of growing interest. Understanding the role of eccentric training and functional resistance training in post-ACLR rehabilitation could provide insights into more effective rehabilitation strategies, improving long-term outcomes and reducing the risk of further injuries.

### AIM

To evaluate the effectiveness of eccentric training and functional resistance training in improving thigh muscle strength following anterior cruciate ligament (ACL) reconstruction.

### METHODOLOGY

A total of 30 post-ACL reconstruction subjects were selected for the study from Kaveri Physio Care, Ambattur based on the inclusion and exclusion criteria. Informed consent was obtained from all participants, and the nature, purpose, benefits, and risks of the study were explained. The subjects were divided into two groups: Group A (Eccentric training group) and Group B (Functional resistance training group). Both groups received interventions for 6 weeks, 4 sessions per week, with each session lasting 30–45 minutes. After the intervention period, post-test values were also noted and statistically analyzed for the group.

### RESULT

Results were analyzed; it can be clearly seen that the outcome measures show significant improvement from pre-test to post-test due to hop test and vertical jump test. When comparing post-test results between the two groups, Group A exhibited significantly greater improvements than Group B. From this result, it has been concluded that eccentric training in the experimental group was more effective than functional resistance training alone in improving thigh muscle strength and functional performance after ACL reconstruction.

**Keywords:** ACL reconstruction, Eccentric training, functional resistance training, hop test and vertical jump test.

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## INTRODUCTION

Anterior Cruciate Ligament (ACL) injuries are among the most common and severe injuries in athletes, particularly those involved in sports requiring sudden changes in direction, jumping, and pivoting <sup>(1)</sup>. These injuries often necessitate surgical reconstruction to restore knee joint stability and function. However, postoperative rehabilitation is crucial, as ACL reconstruction can lead to muscle atrophy and neuromuscular inhibition, particularly affecting the quadriceps and hamstrings <sup>(2, 3)</sup>.

Traditional rehabilitation protocols have primarily focused on concentric exercises, but there is growing interest in incorporating eccentric and functional resistance training to enhance muscle hypertrophy, neuromuscular adaptations, and overall functional recovery <sup>(4)</sup>.

The ACL originates from the anterior intercondylar area of the tibia, just anterior to the anterior horn of the medial meniscus. It courses superiorly, posteriorly, and laterally to insert on the posteromedial aspect of the lateral femoral condyle in the intercondylar notch of the femur <sup>(5)</sup>.

The ACL is composed of two bundles: Anteromedial bundle – Tight in flexion, Posterolateral bundle – Tight in extension <sup>(6)</sup>. These bundles help in stabilizing the knee during movement and work together to prevent excessive anterior tibial translation and rotational instability. The ACL is approximately 38 mm long and 10 mm wide <sup>(7)</sup>. The ACL is the primary restraint against anterior translation of the tibia relative to the femur. It also plays a significant role in rotational stability, preventing excessive internal rotation and valgus stress <sup>(8)</sup>.

**Blood Supply:** Middle genicular artery (a branch of the popliteal artery) provides the main vascular supply to the ACL <sup>(9)</sup>.

**Nerve Supply:** It is innervated by posterior articular branches of the tibial nerve, which carry proprioceptive fibers important for joint stability and reflex responses <sup>(10)</sup>.

ACL injuries often result in significant muscle weakness, particularly in the quadriceps, due to both the injury itself and the subsequent surgery. Quadriceps weakness is one of the primary factors contributing to functional limitations, such as difficulty walking, running, and participating in sports activities. Studies have shown that quadriceps strength deficits are often sustained for months, if not years, after surgery. The hamstrings, although less affected by ACL injury, are also crucial for knee stability and need to be rehabilitated as part of the

overall knee recovery <sup>(11)</sup>.

Thigh muscle strength plays a vital role in the recovery process, as it directly affects knee joint function. The quadriceps and hamstrings work in synergy to control knee motion and absorb forces during dynamic activities. Muscle weakness or imbalance can lead to altered biomechanics, increased stress on the ACL graft, and an increased risk of reinjury. Therefore, restoring strength to these muscles through rehabilitation is essential to achieving full functional recovery after ACL surgery <sup>(12)</sup>. Eccentric training involves the lengthening of muscle fibers under tension and is recognized for its effectiveness in increasing muscle strength and promoting hypertrophy. Unlike concentric training, where muscles shorten as they contract, eccentric contractions occur when a muscle is actively stretched while generating force

<sup>(13)</sup>. Eccentric training is beneficial as it enhances the muscle's ability to control movement during deceleration, which is crucial in dynamic sports movements such as landing from a jump or pivoting <sup>(14)</sup>. For patients recovering from ACL reconstruction, eccentric exercises target the quadriceps, a key muscle group for restoring knee stability and function <sup>(15)</sup>.

Additionally, eccentric training promotes muscle-tendon adaptations, reduces the risk of re-injury, and facilitates a faster return to activity, making it an essential part of progressive rehabilitation programs <sup>(16)</sup>.

One of its main advantages is strengthening muscles without overloading the joint, making it particularly useful in the early stages of rehabilitation when the knee joint is still vulnerable. Research has shown that incorporating eccentric quadriceps exercises into rehabilitation improves muscle strength and function <sup>(17)</sup>. These exercises can be performed in various forms, such as controlled knee extensions, squats, or lunges with a slow lowering phase, using resistance bands, weights, or body weight. The gradual introduction of eccentric loading allows for progressive strengthening while minimizing reinjury risk <sup>(18)</sup>.

Functional resistance training involves exercises that mimic real-life movements and activities. Unlike traditional strength training, which isolates muscle groups, it focuses on improving muscle coordination, joint stability, and overall movement patterns. This training is particularly beneficial for ACL reconstruction patients as it restores knee joint function and prepares them for sport-specific or daily activities <sup>(19)</sup>.

Functional resistance exercises often include multi-joint movements like squatting, lunging, and jumping,

targeting both the quadriceps and hamstrings while engaging stabilizing muscles around the knee and hip. These exercises enhance balance, proprioception, and neuromuscular control, which are crucial for preventing reinjury and improving long-term knee function <sup>(20)</sup>.

Incorporating functional resistance training into rehabilitation bridges the gap between basic muscle strengthening and a functional return to activity. Studies show significant improvements in muscle strength, joint function, and movement efficiency post-ACL reconstruction. Additionally, it enhances dynamic knee stability by improving coordination and muscle synergy. Functional exercises, such as single-leg squats and lateral movements, replicate the stresses and movements encountered in sports or daily activities, helping patients regain their pre-injury level of function <sup>(21)</sup>. Recent evidence suggests that combining eccentric and functional resistance training yields superior results in ACL rehabilitation. This integrated approach enhances muscle strength, joint stability, and functional capacity, addressing both strength deficits and movement patterns <sup>(21)</sup>.

By progressing from simple eccentric exercises to complex functional movements, patients experience a smoother transition from early rehabilitation, focused on strengthening, to later phases emphasizing functional recovery. This approach has been shown to improve both short-term recovery outcomes and long-term performance <sup>(14)</sup>.

Persistent quadriceps weakness after ACL reconstruction remains a significant barrier to full recovery, making the combination of these interventions crucial for optimizing knee function. While existing evidence supports the benefits of eccentric and functional resistance training individually, limited research directly compares their combined or independent effectiveness in improving postoperative outcomes <sup>(22, 23)</sup>. Further exploration of these methods could help clinicians develop evidence-based rehabilitation programs tailored to ACL patients' specific needs <sup>(24)</sup>.

## AIM AND OBJECTIVES

### AIM OF THE STUDY:

The aim of the study is to evaluate the effectiveness of eccentric training and functional resistance training to improve thigh muscle strength and functional performance after ACL reconstruction.

### OBJECTIVE OF THE STUDY:

- To determine the effect of eccentric training to improve thigh muscle strength and functional performance after ACL reconstruction.
- To determine the effect of functional resistance

training to improve thigh muscle strength and functional performance after ACL reconstruction.

- To compare the effect of eccentric training and functional resistance training to improve thigh muscle strength and functional performance after ACL reconstruction.

## BACKGROUND OF THE STUDY

• **Marko D. M. Stojanović et al. (2023)** conducted a study to analyse the effects of eccentric-oriented strength training on return-to-sport criteria in professional team sport players following late-stage anterior cruciate ligament (ACL) reconstruction. ACL injuries often result in prolonged rehabilitation periods, affecting an athlete's ability to regain optimal performance. Traditional strength training approaches focus on general rehabilitation, but eccentric-oriented training has shown promising outcomes in muscle activation and joint stability. The study aimed to compare the effectiveness of six weeks of eccentric-oriented strength training versus traditional strength training in enhancing lower limb strength and functional performance post-ACL reconstruction.

• **Riann M. Palmieri-Smith et al. (2022)** explored the impact of functional resistance training (FRT) on thigh muscle strength after ACL reconstruction. Quadriceps weakness post-ACL reconstruction is a significant concern, often leading to prolonged disability, increased risk of re-injury, and osteoarthritis. The authors proposed that FRT, which integrates resistance training with task-specific motor learning exercises, could improve quadriceps strength more effectively than conventional rehabilitation methods. Their study assessed the effects of FRT on isometric knee extension and flexion strength, using different resistance conditions such as bracing, elastic bands, and target-matched training.

## NEED FOR THE STUDY

Eccentric training and functional resistance training are considered effective rehabilitation techniques for improving thigh muscle strength post-ACL reconstruction. These training methods target muscle activation, enhance neuromuscular control, and facilitate strength recovery, which is crucial for restoring knee function and preventing re-injury. Eccentric training focuses on lengthening the muscle under load, promoting muscle hypertrophy and tendon healing, while functional resistance training mimics real-life movements, improving coordination and joint stability. The study's need is to evaluate the combined impact of

## "Effects Of Eccentric Training And Functional Resistance Training To Improve Muscle Strength And Functional Performance After Anterior Cruciate Ligament Reconstruction"

both training approaches on thigh muscle strength, functional performance, and long-term recovery in patients undergoing ACL rehabilitation

### **METHODOLOGY**

- **STUDY DESIGN:** Experimental study
- **STUDY TYPE:** Pre and post comparative type
- **STUDY METHOD:** Simple random sampling technique
- **SAMPLE SIZE:** 30 Subjects (15 participants in each group)
- **STUDY DURATION:** 4 sessions per week, with each session lasting 30– 45 minutes up to 6 Weeks

### **INCLUSION CRITERIA:**

- Post-ACL Reconstruction after 3months of surgery
- Age group: 20 to 40 years
- Male and female participants
- Isolated ACL injury (no major meniscus/ligament repairs)
- Medically cleared by orthopedic surgeon to begin strengthening exercises
- Moderate muscle strength deficit based on baseline testing
- Ability to follow commands and perform exercises independently
- Non-athletes or recreational athletes returning to physical activity
- Unilateral ACL reconstruction

### **EXCLUSION CRITERIA:**

- Recent ACL Reconstruction >6 weeks

- Previous knee surgeries other than ACL Reconstruction
- History of multiple ligament injuries in the same knee
- Meniscal repairs with restricted post-op rehab protocol
- Neurological deficits affecting lower limb motor function
- Lower limb fractures within the past 12 months
- Known cardiovascular or respiratory illness limiting physical activity
- Bilateral ACL injuries
- Pain above 4 on VAS during testing

### ➤ **OUTCOME MEASURES:**

- Single Leg Hop Test – to assess functional strength and limb symmetry.
- Vertical Jump Test – to evaluate explosive power of quadriceps and gluteal muscles.

### **MATERIALS REQUIRED:**

- Weight cuff
- dumbbells
- Plyometric box
- Stopwatch
- Measuring tape
- Marker cones
- Exercise mat
- Goniometer (for ROM assessment)
- Chair with and without arm rest
- Pen and paper

## RESEARCH PAPER



**Figure 2:** Materials required

### PROCEDURE

A total of 30 post-ACL reconstruction subjects were selected for the study from Kaveri Physio Care, Ambattur based on the inclusion and exclusion criteria. Informed consent was obtained from all participants, and the nature, purpose, benefits, and risks of the study were explained. The subjects were divided into two groups:

- Group A (n=15) – Eccentric training group
- Group B (n=15) – Functional resistance training group

Both groups received interventions for 6 weeks, 4 sessions per week, with each session lasting 30–45 minutes.

### GROUP A – ECCENTRIC TRAINING GROUP

Subjects in Group A performed isolated eccentric quadriceps and hamstring exercises, supervised by a physiotherapist.

Exercises included:

- Eccentric Leg Extension (machine-based or with ankle cuff): 3 sets of 10 reps
- Eccentric Hamstring Curl: 3 sets of 10 reps
- Nordic Hamstring Exercise: 2–3 sets of 5–8 reps
- Step-down exercise (with control emphasis): 3 sets of 10 reps

#### 1. Eccentric Leg Extension:

Sit on the leg extension machine with your legs at 90 degrees. Extend both legs up, then slowly lower the

involved leg only for 3–5 seconds. Assist with the other leg for concentric return. Repeat 10 repetitions, 3 sets.

#### 2. Eccentric Hamstring Curl:

Lie prone on a hamstring curl machine. Curl both legs, then slowly lower the involved leg over 3–5 seconds while holding the weight. Repeat 10 repetitions, 3 sets.

#### 3. Nordic Hamstring Exercise:

Kneel with feet secured under a stable support. Slowly lower your torso forward, resisting with your hamstrings. Catch yourself with your hands and push back to starting position. Do 5–8 reps, 2–3 sets.

#### 4. Step Down Exercise:

Stand on a step. Slowly lower the uninvolved leg down to the floor while maintaining control in the involved leg. Keep hips and knees aligned. Do 10 steps, 10 repetitions.

#### Progression:

Load was increased based on patient tolerance. Ankle cuff weights began at 1 kg and progressed weekly by 0.5–1 kg, not exceeding 5 kg. Exercises were progressed in range, resistance, and control over 6 weeks.

### GROUP B – FUNCTIONAL RESISTANCE TRAINING GROUP

Subjects in Group B were treated using functional resistance training exercises that mimic daily movements and sports activities using ankle weight

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“Effects Of Eccentric Training And Functional Resistance Training To Improve Muscle Strength And Functional Performance After Anterior Cruciate Ligament Reconstruction”

cuffs.

sets of 10 reps

**Exercises included:**

- Sit-to-stand with resistance (ankle cuff 1–5 kg): 3

- Wall Squats with Weight Cuff: 3 sets of 8–10 reps
- Forward and Lateral Step-ups (with weight cuff): 3

sets of 10 reps each side

- Lunges with Resistance: 3 sets of 8–10 reps

**1. Sit to Stand with Resistance:**

Sit on a chair with ankle cuff weights. Stand up slowly using your thigh muscles, pause, and then sit back with control. Repeat 10 repetitions, 3 sets.

**2. Wall Squats with Weight Cuff:**

Stand with your back against a wall, feet hip-width apart. Slide down into a squat while wearing ankle weights. Hold for 5 seconds and return. Repeat 10 repetitions, 3 sets

**3. Forward and Lateral Step-ups:**

Step onto a bench with the involved leg first, then the other leg. Step down with the uninvolved leg. For lateral step-ups, step sideways onto the bench. Repeat 10 steps, 3 sets each direction.

**4. Lunges with Resistance:**

Step forward with the involved leg while wearing an ankle cuff. Lower your back knee close to the ground, then return to standing. Repeat 10 repetitions per leg, 3 sets.

Starting weight cuff resistance was 1 kg, increased weekly based on tolerance by 0.5– 1 kg, not exceeding 5 kg. Movement speed, reps, and complexity were increased over time.

The patients were pre and post assessed with Hop Test and Vertical Jump Test. Both groups received interventions for 6 weeks, 4 sessions per week, with each session lasting 30–45 minutes. The selected exercise protocol was taught to the patient with appropriate repetition and rest, lastly the outcome measure where calculated.

**OUTCOME MEASURES**

Hop Test and Vertical Jump Test will be used as outcome measures.

**HOP TEST:**

The Hop Test is a performance-based assessment commonly used to evaluate lower extremity function, especially after anterior cruciate ligament (ACL) reconstruction. It measures dynamic stability, strength, and neuromuscular control. The test includes variations such as the single-leg hop for distance, triple hop for distance, crossover hop for distance, and 6-meter timed hop.

For the single leg hop for distance, the subject stands on one leg and hops forward as far as possible, landing on the same leg while maintaining balance for at least 2

seconds. The test is repeated three times, and the average distance is calculated. The limb symmetry index (LSI) is used to compare the involved leg with the uninvolved leg and is calculated by the formula:

$$LSI = (\text{distance of involved leg} / \text{distance of uninvolved leg}) \times 100$$

An LSI of 85% or above is generally considered acceptable for return to sport <sup>(34)</sup>.

**VERTICAL JUMP TEST:**

The Vertical Jump Test is a commonly used assessment tool for measuring lower body power and explosive strength, particularly of the quadriceps and calf muscles. It is widely used in athletic and rehabilitation settings. The subject stands flat-footed beneath a measuring device or wall, performs a maximal vertical jump using a countermovement, and touches the highest point they can reach.

The height jumped is measured by the difference between the standing reach and the jump reach. It can be used to monitor improvement in muscle power and to track rehabilitation progress.

A common variation is the Countermovement Jump (CMJ) performed on a force platform or using a Vertec device. Repeated trials are averaged, and normative values differ based on age, gender, and athletic level <sup>(35)</sup>.

**DATA ANALYSIS & INTERPRETATION**

- All statistical analysis was performed on an IBM-compatible microcomputer using the Statistical Package for the Social Sciences (SPSS Version 26.0).
- The level of significance was set at alpha = 0.05. Intra-group comparisons (pre- test vs post-test) within each group were analyzed using the Paired t-test. Inter- group comparisons between the Eccentric Training Group and the Functional Resistance Training Group were analysed using the independent t-test.
- The mean and standard deviation (SD) were calculated for thigh muscle strength pre- and post-intervention. Statistical tests were applied to assess the effectiveness of both training protocols based on changes in outcome measures including single leg hop test, and vertical jump test.

$$SD = \sqrt{\frac{\sum (x_1 - \bar{x})^2}{n-1}}$$

“Effects Of Eccentric Training And Functional Resistance Training To Improve Muscle Strength And Functional Performance After Anterior Cruciate Ligament Reconstruction”

**STATISTICAL ANALYSIS:**

The following statistical tools were employed to analyse the data and testing hypothesis. The microcomputer using the Statistical Package for the Social Sciences (SPSS Version 26.0) was used to calculate and analyse the below mentioned descriptive and inferential statistics

➤ Mean ( $X = \frac{\sum x}{n}$ )

•  $\sum x$  = Sum of all variables

• n = Sample size

➤ Standard deviation

•  $X_1$  = is the mean

• n = is the total number of data points

□ = represents a data point

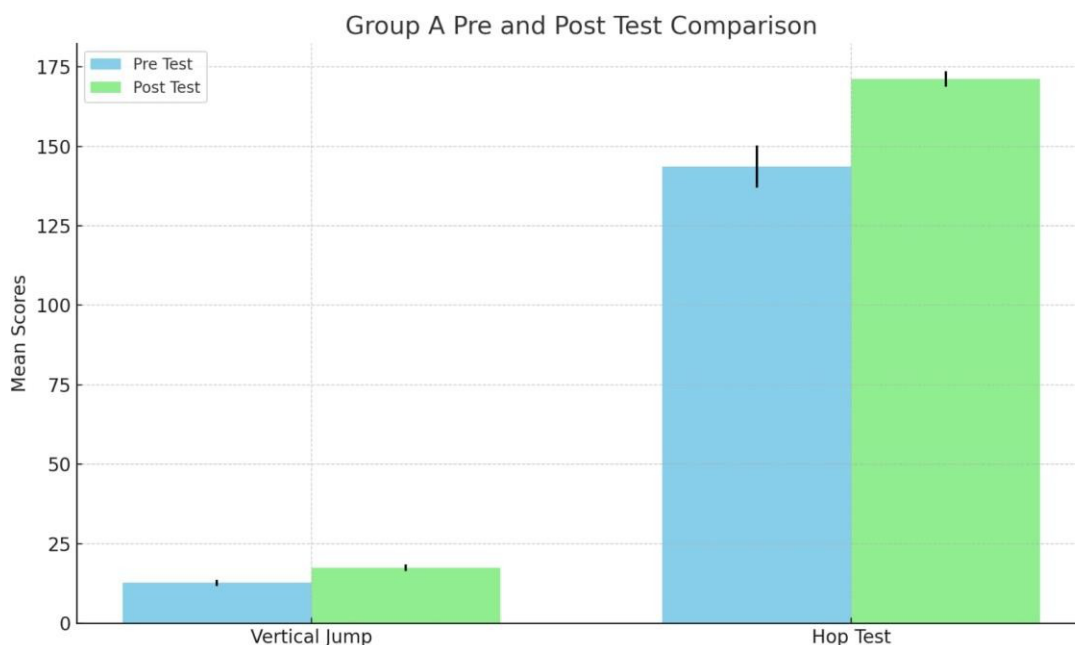
➤ Paired ‘t’ test - The paired “t” test is used to compare the effectiveness of both treatments in both the groups

**TABLE 1: GROUP A PRE AND POST TEST**

OUTCOMES	GROUP A		P VALUE	T VALUE
	PRE TEST (MEAN±SD)	POST TEST (MEAN±SD)		
VERTICAL JUMP	12.7±0.9	17.5±1	0.001	21.3
HOP TEST	143.7±6.6	171±2.5	0.001	15.4

**INTERPRETATION:** According to Table 1 and the graph result of the paired T- test, there is a statistically significant difference between Group A pre and post-test

M=17.5, SD=1; p=0.001, t=21.3) and Hop Test (Pre: M=143.7, SD=6.6; Post: M=171.2, SD=2.5; p=0.001, t=15.4), indicating a significant improvement in both



in the Vertical Jump (Pre: M=12.7, SD=0.9; Post:

outcomes after the intervention.

**GRAPH 1:** Group A pre and post-test of vertical jump test and hop test.

**TABLE 2: GROUP B PRE AND POST TEST**

OUTCOMES	GROUP B		P VALUE	T VALUE
	PRE TEST (MEAN±SD)	POST TEST (MEAN±SD)		

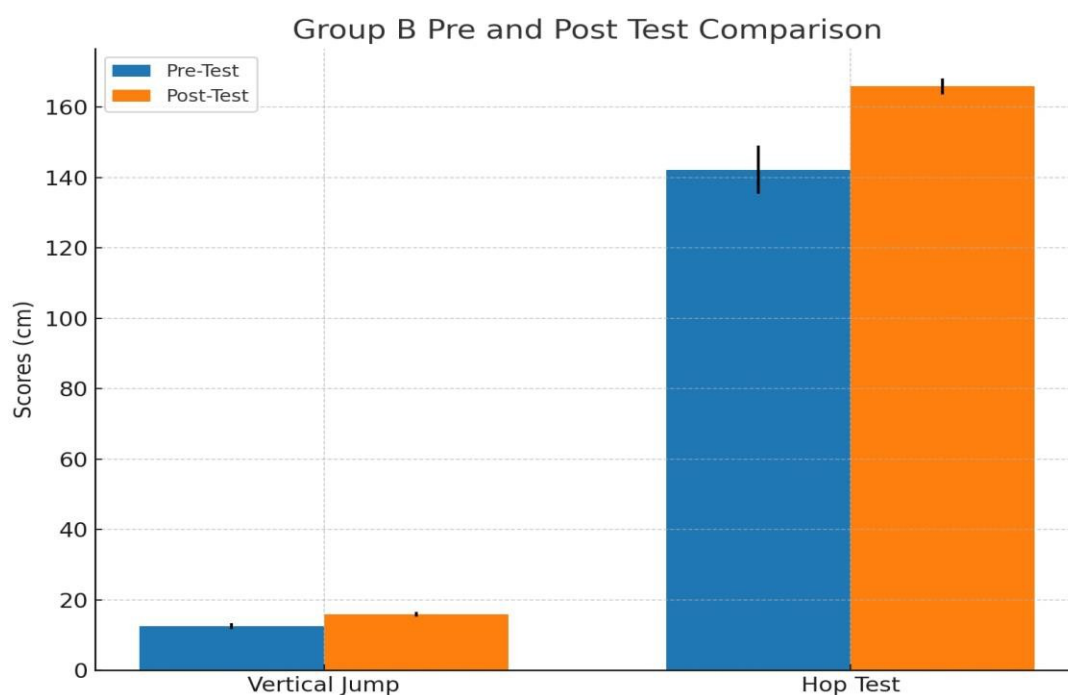
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<b>VERTICAL JUMP</b>	<b>12.5±0.8</b>	<b>15.9±0.7</b>	<b>0.001</b>	<b>11.2</b>
<b>HOP TEST</b>	<b>142.2±6.8</b>	<b>165.9±2.3</b>	<b>0.001</b>	<b>12.1</b>

**Interpretation:** According to Table 2 and the graph result of the paired T-test, there is a statistically significant difference between Group B pre and post-test in the Vertical Jump (Pre: M=12.5, SD=0.8; Post: M=15.9, SD=0.7; p=0.001, t=11.2) and Hop Test (Pre:

M=142.2, SD=6.8; Post: M=165.9, SD=2.3; p=0.001, t=12.1), indicating a significant improvement in both outcomes after the intervention.

“Effects Of Eccentric Training And Functional Resistance Training To Improve Muscle Strength And Functional Performance After Anterior Cruciate Ligament Reconstruction”



**GRAPH 2:** Group B pre and post test of vertical jump test and hop test.

**TABLE 3:** PRE AND POST TEST VALUES OF GROUP A (ECCENTRIC TRAINING) AND GROUP B (FUNCTIONAL RESISTANCE TRAINING)

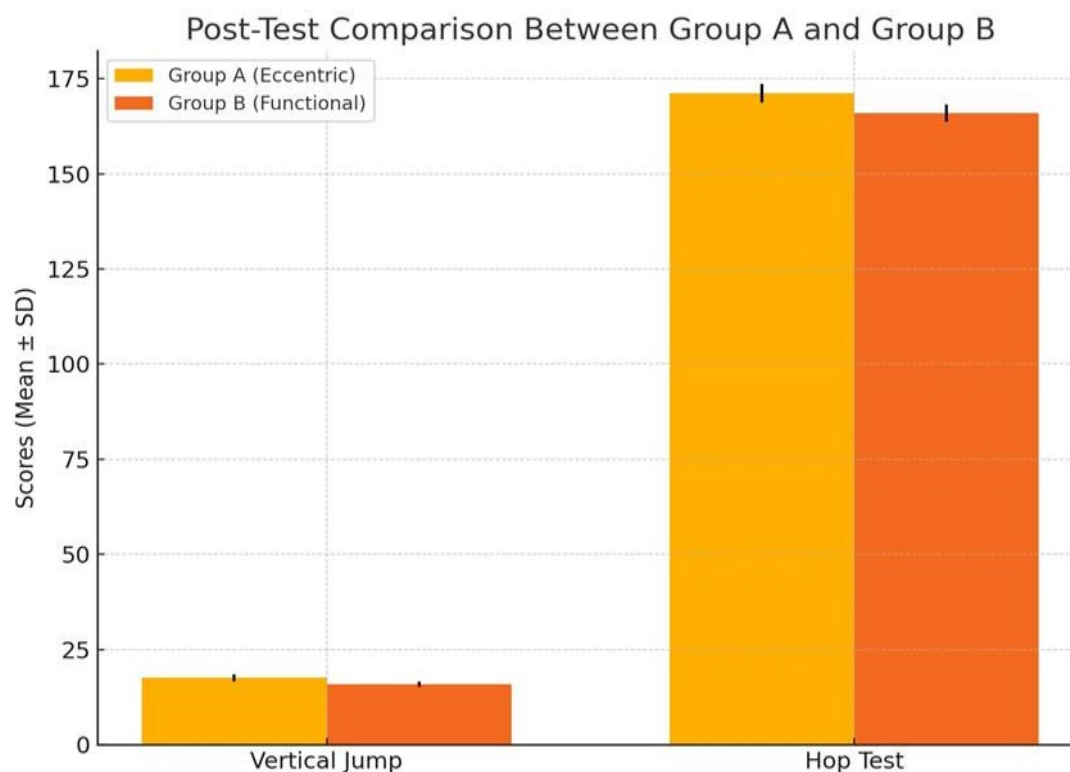
OUTCOMES	POST TEST		P VALUE	T VALUE
	GROUP A (MEAN±SD)	GROUP B (MEAN±SD)		
VERTICAL JUMP	17.5±1	15.9±0.7	0.001	5.02
HOP TEST	171±2.5	165.9±2.3	0.001	6.07

**Interpretation:** According to Table 3 and the graph, the independent t-test showed a statistically significant difference between Group A (Eccentric Training) and Group B (Functional Resistance Training) in both Vertical Jump and Hop Test after the intervention.

- Vertical Jump: Group A (M=17.6, SD=1) demonstrated a significantly greater improvement compared to Group B (M=15.9, SD=0.7), with p=0.001, t=5.02.
- Hop Test: Group A (M=171.2, SD=2.5) also showed

significantly better results than Group B (M=165.9, SD=2.3), with p=0.001, t=6.07.

These findings suggest that Eccentric Training (Group A) was more effective in improving both vertical jump and hop test performance compared to Functional Resistance Training (Group B). The statistically significant p-values (p<0.05) and high t-values indicate a substantial difference between the two groups in post-test outcomes.



**GRAPH 3:** Comparison between group A (eccentric training) and group B (functional resistance training)

## RESULTS

The results indicate significant improvements in both vertical jump and hop test performance within Groups A and B. In Group A, the vertical jump increased from 12.7

± 0.9 cm to 17.5 ± 1 cm ( $p = 0.001$ ,  $t = 21.3$ ), while the hop test improved from 143.7

± 6.6 cm to 171 ± 2.5 cm ( $p = 0.001$ ,  $t = 15.4$ ). Similarly, Group B also demonstrated significant progress, with vertical jump performance rising from 12.5 ± 0.8 cm to 15.9

± 0.7 cm ( $p = 0.001$ ,  $t = 11.2$ ) and hop test scores increasing from 142.2 ± 6.8 cm to

165.9 ± 2.3 cm ( $p = 0.001$ ,  $t = 12.1$ ). When comparing post-test results between the two groups, Group A exhibited significantly greater improvements than Group B. The post-test vertical jump score for Group A (17.5 ± 1 cm) was significantly higher than that of Group B (15.9 ± 0.7 cm) ( $p = 0.001$ ,  $t = 5.02$ ). Likewise, the hop test scores in Group A (171 ± 2.5 cm) were superior to those in Group B (165.9 ± 2.3 cm) ( $p = 0.001$ ,  $t = 6.07$ ).

These findings suggest that while both interventions were effective in enhancing performance, the method used in Group A resulted in significantly greater improvements. The highly significant p-values (0.001) across all comparisons further reinforce the effectiveness of the intervention applied to Group A.

## DISCUSSION

This study was conducted to evaluate the effects of eccentric training and functional resistance training on thigh muscle strength and functional performance in individuals following anterior cruciate ligament (ACL) reconstruction. The aim was to determine whether integrating these training modalities could significantly improve rehabilitation outcomes in the post-operative phase. The results demonstrated a statistically significant improvement in quadriceps strength, hamstring strength, and functional performance in the eccentric training group compared to the functional resistance training group.

Eccentric training has been shown to elicit greater muscle hypertrophy, and strength gains due to the higher mechanical loading placed on muscle fibers during lengthening contractions. In our study, participants in Group A who underwent eccentric training displayed higher gains in isokinetic quadriceps strength at both 60°/s and 180°/s compared to Group B, which received functional resistance training. This finding aligns with studies by Gerber et al. (2009), who concluded that eccentric quadriceps training led to significant improvements in muscle volume and strength in ACL-reconstructed individuals.

The superior outcomes seen in the eccentric training group may be attributed to the increased mechanical tension and neural adaptations elicited by eccentric

muscle contractions. Eccentric exercises promote greater activation of type II muscle fibers and stimulate satellite cell proliferation, which enhances muscle repair, hypertrophy, and tendon remodelling (Gerber et al., 2009; Kongsgaard et al., 2009). These physiological mechanisms likely contributed to the increased thigh muscle strength observed in the eccentric group.

In addition, eccentric training has been found to reduce post-operative quadriceps inhibition, a major barrier to recovery following ACL reconstruction. Lepley et al. (2015) emphasized that eccentric loading helps restore quadriceps activation, thereby accelerating functional recovery. Similarly, Gokeler et al. (2019) suggested that eccentric exercises improve neuromuscular control by enhancing corticospinal excitability and muscle fiber recruitment. Functional resistance training, while effective, is designed more toward improving coordinated movement patterns, neuromuscular control, and joint proprioception. In our study, Group B participants demonstrated improvement in functional performance tests such as the single-leg hop and timed up-and-go test, though to a lesser extent than Group A. These results align with the findings of Augustsson et al. (2006), who emphasized the role of functional resistance exercises in improving postural control and kinetic chain coordination, especially during late-stage rehabilitation.

The differences in outcomes between the two groups reflect the principle of training specificity. Eccentric training, which directly targets muscle strength and hypertrophy, may be more beneficial during the mid-phase of ACL rehabilitation when strength deficits and muscle atrophy are major concerns (Lepley et al., 2015). In contrast, functional resistance training may serve as a complementary modality in the late phase of rehabilitation, when the focus shifts to sport-specific activities, proprioception, and movement control (Augustsson et al., 2006; Clark et al., 2012).

Eccentric training also offers additional benefits in terms of bilateral strength symmetry. According to Lepley and Palmieri-Smith (2016), eccentric exercises significantly reduce strength deficits between the involved and uninvolved limbs, a key factor in minimizing re-injury risk and optimizing return-to-sport readiness. Persistent quadriceps weakness post-surgery has been associated with poor long-term knee function and higher osteoarthritis risk (Schmitt et al., 2012). Therefore, improving muscle balance through eccentric interventions becomes critically important.

Furthermore, studies by Meyer et al. (2018) highlighted that eccentric loading results in improved muscle-tendon unit stiffness and collagen synthesis, enhancing tendon

resilience and joint stability. This makes eccentric training a superior option not only for muscle strength but also for structural joint support post-surgery. In contrast, Pincivero et al. (2017) noted that while functional resistance training improves multi-joint coordination and movement efficiency, it may not offer the same isolated strength benefits essential in early post-operative phases.

Our results also confirm the findings of Clark et al. (2012), who reported that functional resistance training is effective in improving dynamic control and reducing injury risk during return-to-sport assessments. However, the combination of both modalities may yield the best functional outcomes by addressing both muscular strength and neuromuscular performance.

Despite these positive outcomes, some limitations must be acknowledged. The intervention duration was limited to six weeks, which may not fully reflect long-term benefits of either training approach. The relatively small sample size and the lack of objective monitoring of participant adherence outside supervised sessions may also influence the generalizability of results. Future studies with larger cohorts, extended follow-up, and controlled intensity progression are recommended to validate these findings and explore long-term effects.

Clinically, this study highlights the importance of integrating eccentric exercises during early and mid-stage rehabilitation to address strength deficits and restore muscle function. Subsequently, incorporating functional resistance training in the later stages can help improve neuromuscular control, dynamic balance, and readiness for sport-specific activities. A sequential or combined protocol may offer a comprehensive and efficient approach for maximizing recovery and reducing re-injury risk post-ACL reconstruction.

In conclusion, this study demonstrates that eccentric training is more effective than functional resistance training in improving thigh muscle strength and functional performance in patients following ACL reconstruction. Nonetheless, functional resistance training remains vital for enhancing proprioception and dynamic movement control. A combined, phase-specific strategy incorporating both modalities may provide the most optimal pathway for full functional recovery and safe return to activity.

## CONCLUSION

The study revealed significant improvements in both vertical jump height and hop test performance within Group A and Group B following their respective training protocols. Both groups demonstrated progress in muscle strength and functional performance; however, the improvements observed in Group A were more

pronounced. From this result, it has been concluded that eccentric training in the experimental group was more effective than functional resistance training alone in improving thigh muscle strength and functional performance after ACL reconstruction. The eccentric training protocol led to greater enhancement in vertical jump height, hop test performance and overall muscular strength, thereby contributing to a more efficient recovery and functional return in post-ACL reconstructed individuals.

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"Effects Of Eccentric Training And Functional Resistance Training To Improve Muscle Strength And Functional Performance After Anterior Cruciate Ligament Reconstruction"

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