Determining Short Term Effects of Plyometric Training Program and Blood Flow Restriction Training on Dynamic Stability and Functional Performance in Players with ACL Reconstruction

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Abstract

Background: Anterior cruciate ligament (ACL) injuries are among the most common and debilitating musculoskeletal injuries in athletes, often resulting in impaired joint stability, neuromuscular control, and reduced functional performance which delay return to sport. Despite advancements in post ACLR rehabilitation, optimal rehabilitation strategies are critical to restore pre-injury athletic function and ensure safe and accelerated return to sport. Plyometric training enhances neuromuscular coordination and dynamic stabilization through explosive movements, while blood flow restriction training (BFRT) facilitates muscle hypertrophy and strength gains at low loads. Yet evidence of integrating rehabilitation strategies like plyometric and blood flow restriction training (BFRT) for optimize recovery is limited. The integration of these modalities may provide synergistic benefits in accelerating functional recovery.

Aim: The aim of the present study was to evaluate the short-term effects of plyometric training program and BFRT interventions on dynamic stability and functional performance in players with ACL reconstruction.

Methodology: Thirty ACL-reconstructed participants including male and female (aged 18–35 years) were randomly assigned (using convenient sampling) to Group A (Conventional Rehabilitation) and Group B (Plyometric + BFRT), with 15 participants in each group, undergoing a 12-week intervention, three sessions per week. YBT and IKDC assessments were conducted at baseline, 6 weeks, and 12 weeks to evaluate dynamic stability and functional performance, respectively.

Results: Both groups demonstrated statistically significant improvements over time in YBT and IKDC scores ($p<0.05$). Group B exhibited significantly greater gains at both 6 and 12 weeks compared to Group A ($p<0.01$), indicating superior enhancement in dynamic stability and functional outcomes with the combined intervention.

Conclusion: The present study concluded that plyometric training and BFRT is more effective than the conventional protocols in improving dynamic stability and functional performance among players with ACL reconstruction rehabilitation. Incorporating these evidence-based approaches may optimize early recovery and facilitate a safer and earlier return to sport.

Keywords: ACLR, Dynamic Stability, Functional Performance, Y-Balance Test, IKDC Score, Blood Flow Restriction Training, Plyometric Training.

1. INTRODUCTION

In the last decade, India has become a huge global hub of sports which has influenced a lot people to participate in sports for both, professionally and for leisure as well. With the significant increase in participation of the people in sports, there has been noticeable hike in sports related injuries, ranked as the second highest (21%) cause of injury[1]. Anterior cruciate ligament (ACL) injuries are among the most frequent and functionally limiting musculoskeletal injuries, showing a rising trend globally, particularly among the athletic population engaged in high-risk sports involving cutting, pivoting, and jumping movements[2]. According to M.S. Dhillon, et al, in India, the prevalence of ACL injuries is significantly high in contact sports such as kabaddi, with reported rates reaching 89.47% among athletes[3]. Globally, the incidence of ACL tears ranges from 400 per 100,000 populations annually in adolescents, with a higher rate observed in females post-puberty[4]. Notably, sports like football and basketball exhibit higher injury rates 14.9% in female football players and 7.9% in female basketball players[5]. Despite improvements in surgical techniques, the re-injury rate post-ACL reconstruction remains concerning, reported as high as 77% during return-to-sport phases[6].

The anterior cruciate ligament (ACL) is one of the key stabilizing structures of the knee joint, preventing excessive anterior translation and rotational displacement of the tibia relative to the femur whereas structurally, it spans from the medial aspect of the lateral femoral condyle to the anterior intercondylar area of the tibia[7]. ACL tears are systematically categorized based on their anatomical location along the distal-to-proximal length of the ligament. Type I tears were defined as proximal avulsion injuries occurring in the region extending beyond 90% of the ligament's total length. Type II tears represented proximal tears located between

75% and 90% of the distal-to-proximal extent. Type III tears involved the midsubstance of the ligament and are situated between 25% and 75% of its length. Type IV tears were characterized as distal tears found between 10% and 25% of the ligament's length. Type V tears are classified as distal avulsion injuries occurring within the distal-most 10% of the ligament. Additionally, Type I and Type V tears are further sub-classified into either soft tissue avulsion or bony avulsion types based on the nature of the tissue involved[8].

However, following reconstructive surgery, limitations have been documented in the muscular and sensory processes, and it has been proposed that the capacity to conduct functional performance and balance may be diminished. Regaining normal range of motion, knee joint stability, muscle strength, and neuromuscular control, all of which support normal functional performance is the ultimate objective in this situation following ACL reconstruction (ACLR) and rehabilitation[9]. Consequently, rehabilitation following ACL reconstruction must not only focus on restoring joint range of motion and strength but also target neuromuscular retraining to restore dynamic joint stability and functional movement patterns[10]. Dynamic stability is a critical determinant of athletic performance and injury prevention[11]. The Y-Balance Test (YBT) is a validated clinical tool used to assess dynamic balance and postural control, reflecting the lower limb's neuromuscular efficiency and symmetry[12]. Functional performance, on the other hand, encompasses the athlete's ability to execute sport-specific tasks efficiently and without compensation[11]. The International Knee Documentation Committee (IKDC) subjective score is a comprehensive and standardized tool used to evaluate functional status, symptoms, and sports activity limitations following ACLR[13]. In order to improve athletic outcomes i.e. return to pre-injury level of athletics after ACL reconstruction, there is a great need to follow disciplined criteria based rehabilitation. There exists an inconsistent body of literature concerning a rehabilitation protocol based on criteria following an ACL reconstruction, despite the high prevalence of ACL reconstruction in the literature. Patients participate in rigorous rehabilitation regimens after surgery in an effort to improve the afflicted limb's strength, stability, flexibility, and muscle power. With the current focus on assisting patients to attain functional performance, range of motion, progressive muscular strengthening, dynamic stability, neuromuscular control, and a safer return to sports through exercise, recent advancements in rehabilitation following ACL surgery are still being made. One highly valued element of advanced rehabilitation after ACL reconstruction is the use of plyometric training and BFRT.

Plyometric training is defined as a type of explosive movement training that involves rapid stretching and shortening of muscles, it is high-intensity explosive exercise designed to enhance the stretch-shortening cycle (SSC) of muscles, thereby improving power, speed, and neuromuscular performance[14]. The term "plyometrics" was first coined in 1975 by Fred Wilt, a former American track and field coach, after observing the training methods used by Eastern European athletes, particularly in the Soviet Union[14-18]. However, the foundational principles date back to the 1960s under the work of Dr. Yuri Verkhoshansky, a Soviet sports scientist who is widely regarded as the "father of plyometrics."[19, 20]. Verkhoshansky introduced "shock training" or depth jumping, which involved jumping off a height and immediately rebounding upwards[21]. This technique exploited the physiological benefits of the muscle's eccentric-concentric transition, enhancing the neuromuscular reflexes and elastic energy storage[21]. It is particularly effective in improving neuromuscular control, muscle power, balance, and proprioceptive feedback. Physiologically, plyometric movements like jumps and hops stimulate the Golgi tendon organ and muscle spindles, promoting better reflexive control and stabilization during dynamic tasks[22]. Over time, plyometric training has evolved to include a wide range of drills such as squat jumps, bounding, single-leg hops, and lateral jumps, all aimed at improving proprioception, joint stabilization, and functional agility, critical for rehabilitation post-ACL reconstruction.

Blood Flow Restriction Training (BFRT), also known as occlusion training, originated in Japan in the 1960s through the accidental observation of Dr. Yoshiaki Sato, a young medical student at the time[23]. During a prolonged Buddhist ceremony in which participants sat in a traditional kneeling posture for extended periods, Sato noticed a numb, swollen sensation in his lower legs similar to what he typically experienced after resistance training. This sensation sparked the idea that restricted blood flow to the muscles might create a similar stimulus as high-load strength training, even under low-load conditions[23]. Sato began experimenting with vascular occlusion and exercise, eventually formalizing his methods under the name "Kaatsu," meaning "added pressure" in Japanese. BFRT gained scientific validation in the 2000s, particularly through the work of Dr. Jeremy Loenneke and Dr. Takashi Abe, who contributed extensively to understanding its application in both healthy populations and clinical rehabilitation settings[24]. The concept involves the application of a pneumatic cuff or band to the proximal portion of the limb to partially restrict arterial inflow and fully restrict venous outflow during low-load resistance exercises (typically 20–30% of 1-RM) [25]. This restriction induces cellular hypoxia, leading to the accumulation of metabolic byproducts such as lactate, which in turn stimulates anabolic hormonal responses notably increased levels of growth hormone, IGF-1, and muscle protein synthesis through pathways like mTOR and MAPK[24].

2. METHODOLOGY:

This experimental study was conducted at the Department of Sports Physiotherapy, DAV Institute of Physiotherapy and Rehabilitation, Jalandhar. A total of 30 participants (both male and female) aged between 18 and 35 years, who had undergone anterior cruciate ligament reconstruction (ACLR) using patellar tendon, quadriceps tendon, hamstring tendon, or peroneus longus autograft, were recruited using convenient sampling. Participants were randomly divided into two groups: Group A (n = 15) received conventional rehabilitation, while Group B (n = 15) received a combination of plyometric training and blood flow restriction training (BFRT). Both groups followed a supervised rehabilitation protocol three times per week for 12 weeks. The inclusion criteria comprised participants who had completed the initial post-operative rehabilitation (Phase 2), demonstrated full active range of motion, had no episodes of knee instability in the prior four weeks, and were willing to return to sports activity. Participants with associated fractures, uncontrolled comorbidities (e.g., diabetes, hypertension), lower limb neurological disorders, deep vein thrombosis, severe patellofemoral pain, or recent knee infections were excluded from the study.

All assessments were conducted under standardized environmental conditions by blinded evaluators, ensuring consistency, objectivity, and reducing assessor bias. The tests were repeated at all three time points to evaluate changes over the intervention period i.e. baseline (pre-intervention), 6th week (mid-intervention), and 12th week (post-intervention). The data was collected using International Knee Documentation Committee (IKDC) to evaluate functional performance. It is a subjective knee evaluation form which is a validated, self-administered questionnaire designed to assess symptoms, activity limitations, and sports-related functional outcomes in individuals with knee injuries. The score is expressed as a percentage, with higher values indicating superior perceived knee function and lower symptom burden. Participants completed the form independently, under supervision to ensure completeness and accuracy of data[13].

For the assessment of dynamic stability, the Y-Balance Test (YBT) was employed. The test was performed with the participant standing on the involved (ACL-reconstructed) limb while reaching in three directions i.e. anterior, posteromedial, and posterolateral using the contralateral leg. A standardized demonstration was provided, followed by three practice attempts to ensure familiarization. Subsequently, three valid trials were recorded in each direction[11]. The average reach distance was calculated and normalized to the participant's limb length using the formula:

Composite Score (%) = [(Anterior + Posteromedial + Posterolateral) / (3 × Limb Length)] × 100. This scoring method accounts for individual anthropometric differences, facilitating accuracy between-subject comparisons.

2.2 Procedure:

Group A procedure:
Warm up: light jogging, dynamic stretching * 10-15 mins, Electrotherapy: Russian currents with squats * 20 mins, Exercise regime: conventional strength, power, speed exercises * 50 min approximately, Cool down period: walking, stretching * 10 mins

Electrotherapy: Russian currents, its use are well admired as muscle strengthening modality. It is a medium frequency current. The surface carbon electrodes were placed with a focus on the Quadriceps muscles; four electrodes around the muscle belly of the quadriceps muscles. The frequency were set at 2,500 Hz i.e. 50 pulse /sec, with an on /off-ratio of 10/10 sec. It is applied for 20 minutes. Exercise dosage is given according to individual by calculating training load (TL); it is quantification which is critical for optimizing performance and preventing overtraining. Rating of Perceived Exertion (RPE) has been used to monitor internal load. Athletes were assigned a subjective intensity score post-session, responding to the question, "How was your workout?" on a given scale. Training load was calculated by multiplying the RPE score by session duration (in minutes)[26-28].

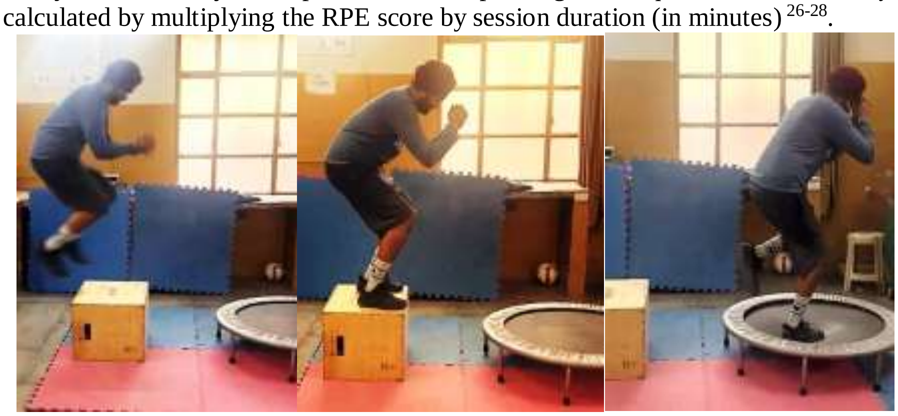


Figure 1: Jump and land unilateral on trampoline

Figure 2: Swiss ball prone jack knife

Figure 3: Lunge push back

Group B procedure:

Warm up: light jogging, dynamic stretching * 10-15mins, Electrotherapy: Russian currents with squats * 20 mins, Exercise regime: plyometrics + Blood Flow Restriction Training* 50 min approximately, Cool down period: walking, stretching *10 minutes.

Plyometric training: It was divided into 3 progressive phase, first phase was from week 1 to week 4, second phase was from week 5 to week 8 and third phase was from week 9 to week 12. With every progressive phase there will be increased difficulty level in exercise regime. The patient met the progression criteria after every phase to enter next phase of plyometric training. The inter-set rest time was 2-4 minutes to avoid muscle fatigue. There must be 48 to 72 hours adequate rest between workout sessions for muscles to get proper recovery period.

The BFR cuff (air tourniquet cuff) was securely wrapped around the proximal portion of the thigh and the cuffs were then inflated manually using a handheld pump to a pressure corresponding to 60-80% Limb occlusion pressure[30-32]. LOP was measured using pulse oximeter, for the safe and effective application of BFRT[29]. A pulse oximeter was placed on the great toe of the same leg where cuff is worn. The participant was positioned comfortably in a supine position and limb to be assessed was supported and relaxed throughout the procedure to minimize sympathetic stimulation and enhance measurement accuracy. Ensure the pulse oximeter in place and displaying a stable signal, baseline pulse waveform and oxygen saturation (SpO_2) was confirmed. It was used to observe the pulsatile waveform or plethysmographic trace which served as the primary indicator for arterial blood flow to the distal limb. The cuff was gradually inflated with increments of 10–20 mmHg. At each pressure increment, the pulse oximeter waveform was carefully monitored until the pulse waveform completely disappeared, indicating arterial occlusion[29]. Inflation was ceased immediately upon loss of the waveform. The exact pressure (in mmHg) at which the signal disappeared was recorded as the LOP. Cuffs were deflated before the first set of each exercise, and remained deflated during the inter-set recovery periods. The exercises were progressed by increasing the frequency week wise.

Figure 4: Measuring LOP using pulse oximeter

Figure 5: Squats with BFR Cuff

Figure 6: Zig – zag dribbling drills with BFR Cuff

3. RESULTS:

The present experimental study determines short term effects of blood flow restriction training and plyometric training program on dynamic stability and functional performance in players with ACL reconstruction. Data analysis was conducted following the collection of outcome measure scores for both groups. The collected data were systematically organized into a master chart. Statistical analysis was carried out using SPSS software version 22.0. Both intragroup (within-group) and intergroup (between-group) comparisons were performed to evaluate the effects of the interventions. The continuous data were summarised in Mean ± SD (standard deviation) whereas discrete (categorical) in number (n) and percentage (%). The following tests were used:

i. Two independent groups were compared by Student's t test. Groups were also compared by two factor (period x group) repeated measures analysis of variance (RM ANOVA)
ii. Tukey's HSD post hoc test for inter-group analysis after ascertaining normality by Shapiro-Wilk's test and Homogeneity of variance between groups by Levene's test.
iii. Categorical groups were compared by the chi-square ($\chi 2$) test.
iv. The level of significance selected for the study was $p<0.05$ (two-tailed ($\alpha=2$) was considered statistically significant)

Variables:

1) Dynamic stability
2) Functional performance

Days of Data collection:

i. Day 1st Pre-treatment session
ii. Week 6th Post-treatment session
iii. Week 12th Post-treatment session

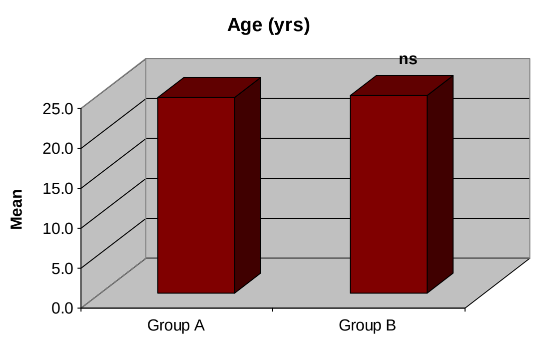
3.1 Demographic Characteristics

The demographic characteristics of Group A and Group B were comparable in terms of age and gender. The age of Group A and Group B ranged from 21-30 and 18-30 years, respectively. The mean age was 24.47 ± 2.85 years in Group A and 24.73 ± 3.51 years in Group B, with a male predominance in both groups. Group A had 5 females and 10 males, while Group B had 3 females and 12 males. Statistical analysis showed no significant difference (P > 0.05) in age or gender between groups, indicating that both groups were age and gender matched, minimizing potential influence on study outcomes.

Table 1: Demographic characteristics of two groups

Variable	Group A (n=15) (%)	Group B (n=15) (%)	t/χ^2 value	*P* value
Age (years)	24.47 ± 2.85	24.73 ± 3.51	0.23	0.821
Gender:				
Female	5 (33.3)	3 (20.0)	0.68	0.409
Male	10 (66.7)	12 (80.0)		

The age of two groups were summarised in Mean ± SD and compared by independent Student's t test where gender were summarised in number (n) and percentage (5) and compared by χ^2 test.



^{ns}P > 0.05- as compared to Group A

Figure 7: Mean age of two groups.

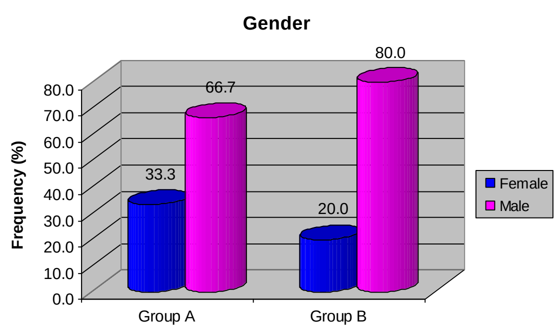


Figure 8: Distribution of gender of two groups

Outcome Measures: Y-balance

The pre and post (6 and 12 week) rehabilitation Y-balance scores of both groups showed marked improvement, with higher scores in Group B than Group A. Intra-group Tukey test showed significant (P < 0.001) improvements at both 6 and 12 weeks compared to baseline, and further improvement at 12 weeks compared to 6 weeks. Inter-group comparison showed similar baseline and 6-week scores (P > 0.05), but significantly higher (P < 0.01) scores in Group B at 12 weeks. The net improvement in dynamic stability was 3.6% higher in Group B (14.8%) than in Group A (11.2%).

Time Period	Group A (n=15)	Group B (n=15)
Baseline	74.33 ± 4.34	77.40 ± 6.68
6 week	78.93 ± 3.97	84.27 ± 5.89
12 week	83.67 ± 3.68	90.87 ± 5.25

The Y-balance score of two groups were summarised in Mean ± SD.

Table 2: Y-balance score (%) of two groups over the periods

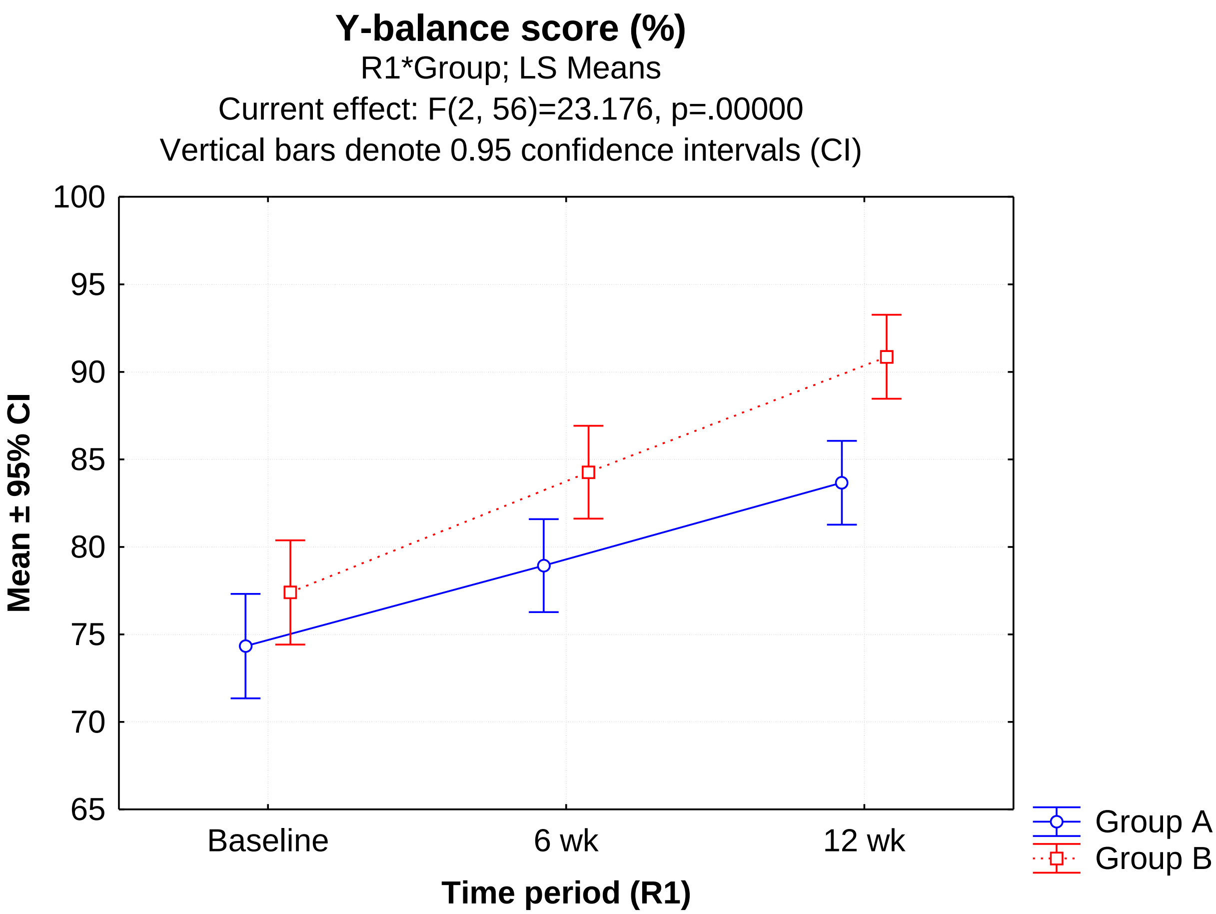
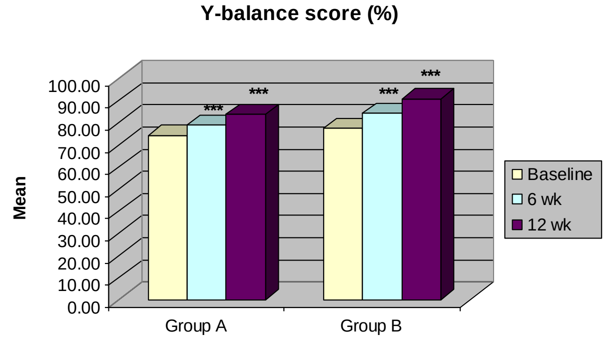


Figure 9: Mean Y-balance score of two groups over the periods.

Comparison	Group A		Group B	
	Mean difference	*P* value	Mean difference	*P* value
Baseline vs. 6 week	4.60	< 0.001	6.87	< 0.001
Baseline vs. 12 week	9.33	< 0.001	13.47	< 0.001
6 week vs. 12 week	4.73	< 0.001	6.60	< 0.001

Table 3: For each group, comparison (*P* value) of difference in mean Y-balance score (%) between periods by Tukey test

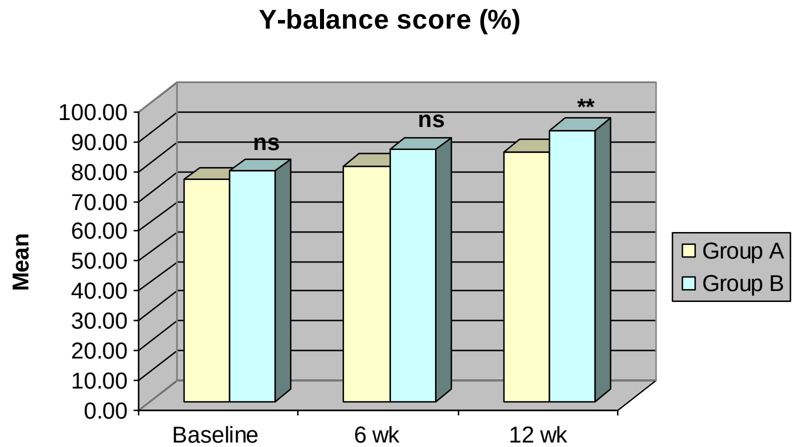


***$P < 0.001$- as compared to Baseline

Figure 10: For each group, comparisons of difference in mean Y-balance score between periods.

Time period	Comparison (Group A vs. Group B)	
	Mean difference	***P* value**
Baseline	3.07	0.572
6 week	5.33	0.073
12 week	7.20	0.006

Table 4: For each period, comparison (*P* value) of difference in mean Y-balance score (%) between groups by Tukey test



ns$P > 0.05$ or **$P < 0.01$- as compared to Group A

Figure 11: For each group, comparisons of difference in mean Y-balance score between periods.

IKDC

The pre and post (6 and 12 week) rehabilitation IKDC scores of both groups showed gradual improvement over time, with higher scores in Group B than Group A. Intra-group Tukey test showed significant ($P < 0.001$) improvements at both 6 and 12 weeks compared to baseline, and further improvement at 12 weeks compared to 6 weeks. Inter-group comparison showed similar baseline scores ($P > 0.05$), but significantly higher scores in Group B at 6 weeks ($P < 0.05$) and 12 weeks ($P < 0.01$). The net improvement in functional performance and return to sports was 6.9% higher in Group B (25.1%) than in Group A (18.2%).

The IKDC score of two groups were summarised in Mean ± SD.

Time Period	**Group A (n=15)**	**Group B (n=15)**
Baseline	66.20 ± 6.72	67.13 ± 6.14
6 week	73.53 ± 4.44	79.67 ± 6.77
12 week	80.93 ± 3.90	89.67 ± 4.40

Table 5: IKDC score (%) of two groups over the periods

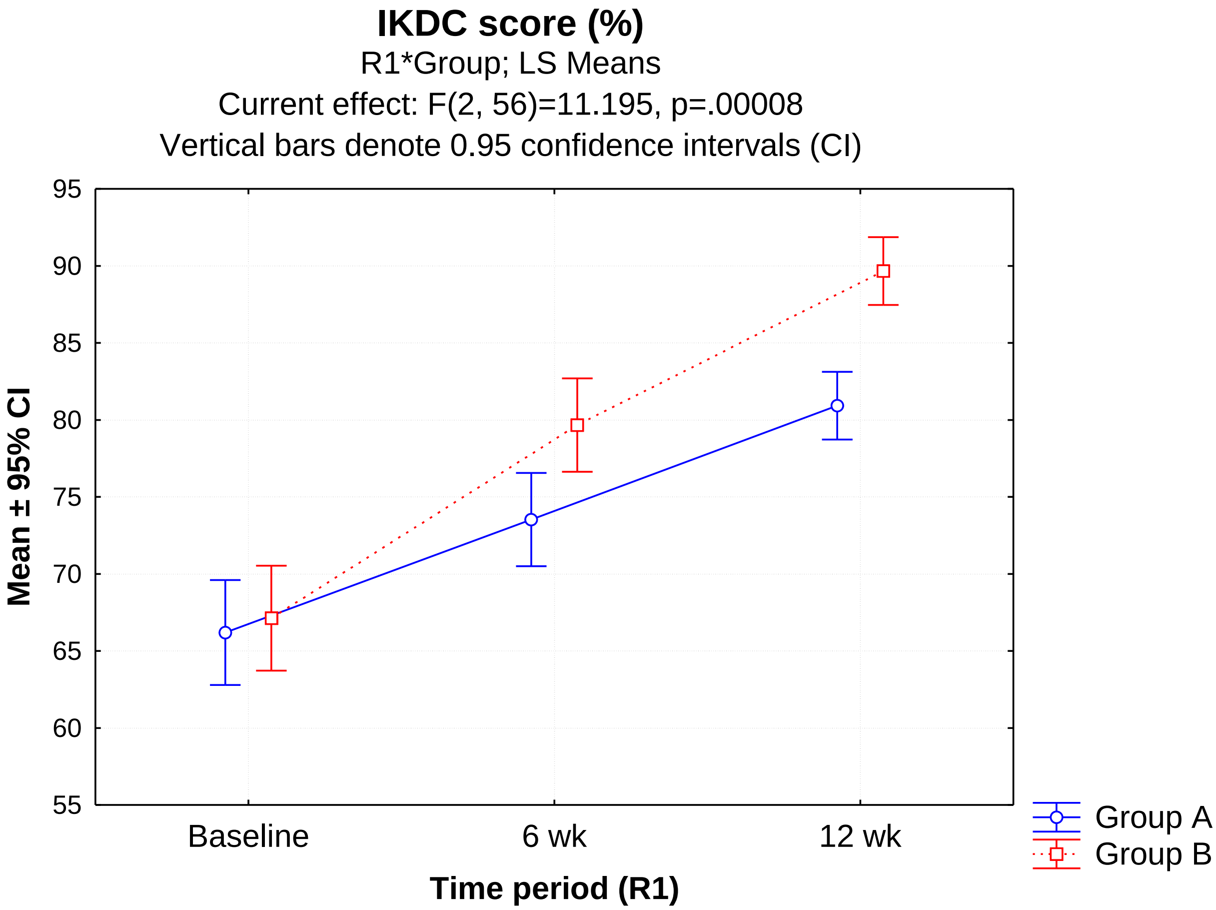
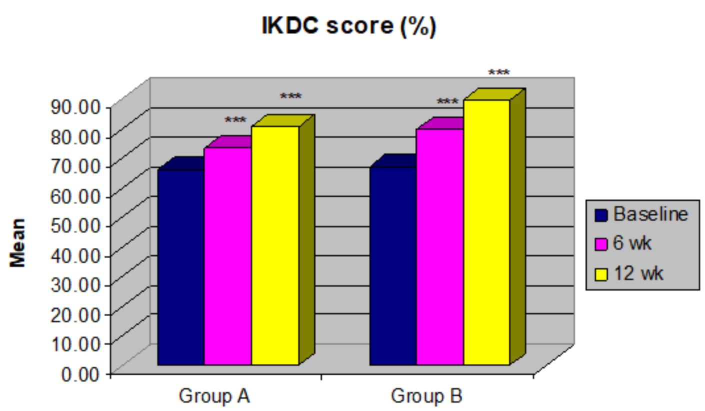


Figure 12: Mean IKDC score of two groups over the periods.

Comparison	Group A		Group B	
	Mean difference	*P* value	Mean difference	*P* value
Baseline vs. 6 week	7.33	< 0.001	12.53	< 0.001
Baseline vs. 12 week	14.73	< 0.001	22.53	< 0.001
6 week vs. 12 week	7.40	< 0.001	10.00	< 0.001

Table 6: For each period, comparison (*P* value) of difference in mean IKDC score (%) between periods by Tukey test

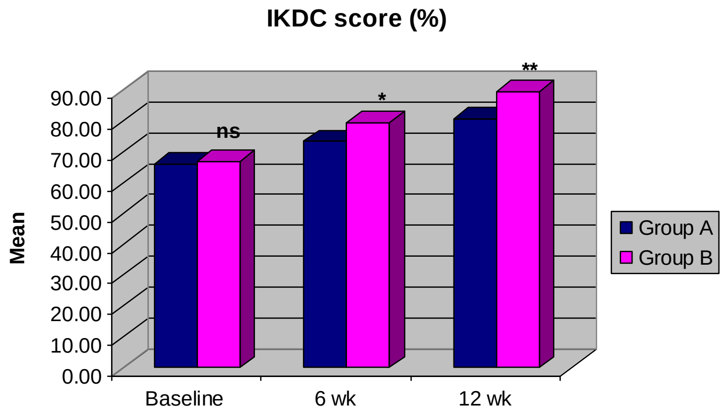


***$P < 0.001$- as compared to Baseline

Figure 13: For each group, comparisons of difference in mean IKDC score between periods.

Time period	Comparison (Group A vs. Group B)	
	Mean difference	*P* value
Baseline	0.93	0.997
6 week	6.13	0.043
12 week	8.73	0.001

Table 7: For each period, comparison (*P* value) of difference in mean IKDC score (%) between groups by Tukey test



$^{ns}P > 0.05$ or $^{*}P < 0.05$ or $^{**}P < 0.01$ - as compared to Group A

Figure 14: For each group, comparisons of difference in mean IKDC score between periods.

DISCUSSION

This study aimed to evaluate the short-term effects of combining blood flow restriction and plyometric training on dynamic stability and functional performance in athletes' post-ACL reconstruction. We hypothesized that this combined approach would significantly enhance recovery outcomes. Using Y-Balance Test and IKDC Score as outcome measures, results showed significant improvements in both groups, with the experimental group demonstrating superior gains. From the analysis, we found that both the conventional and experimental group well performed after the ACL reconstruction in terms of strength, balance, coordination and explosive power. After extensive literature search, the present study may be the first study in India, in our knowledge that appraise the existing rehabilitation protocol for ACLR like BFRT, high intensity resistance exercise, plyometrics, electrotherapy, established conventional rehabilitation protocol by various researchers in published literature among sports person with intention to return to sports. In nutshell, the results of our study demonstrates that while both groups showed significant improvements (p<0.01) over the 12-week intervention period, experimental group exhibited superior gains across all parameters.

The impact of Russian current expert modes on quadriceps muscle torque in healthy persons was investigated by Hasan et al. in 2024. They studied 48 college students in a single-blind, randomized control trial. Due to its high tolerance and minimal pain provocation, Russian currents, a well-known neuromuscular electrical stimulation that operates at 2500 Hz, have shown a notable increase in strength when compared to standard exercises[33]. The inclusion of Russian currents stimulation may be a differential factor among previous studies by various researchers and our research protocol. Besides the therapeutic benefit of pain relief in early post-operative days, it also helps to improve muscle built. As the pain reduces and muscle mass improves, this maybe a factorial for improving functional scores among both groups of ACLR players. Our outcome measures are supported by Akinoglu et. al. (2020)[34] as this medium frequency stimulation specifically employs to treat hamstring and quadriceps muscle group to prevent arthrogenic inhibition following ACLR. Russian stimulation demonstrates a higher evidence for functional recovery among sports person. Post ACLR rehabilitation is essential for restoring joint function and minimizing the risk of re-injury. Conventional rehabilitation protocols primarily focus on progressive range of motion (ROM), strengthening, and proprioceptive training. However, re-injury rates remain a concern. Traditional methods in terms of muscle strengthening, restoring ROM and being without pain during physical activity may not sufficiently prepare athletes for the high demands of competitive sports. In response, emerging training techniques, advancement in surgical techniques, molecular understanding of ACL graft helps scientist and along with randomized control trial studies among various rehab protocol and their favorable outcome, such as plyometric and blood flow restriction (BFR) training are implemented in recent years. Plyometric training targets the stretch-shortening cycle of muscles, thereby enhancing power, coordination, and neuromuscular control[22]. BFR training, on the other hand, facilitates muscle hypertrophy and strength gains at significantly lower loads[35].

The Y-Balance Test (YBT) is a reliable tool for assessing dynamic postural control, which is critical for injury prevention and safe return to sport following ACL reconstruction (ACLR). In this study, both the conventional rehabilitation group (Group A) and the experimental group (Group B) which received combined plyometric and blood flow restriction training (BFRT) demonstrated significant improvements in YBT scores over a 12-week period. However, Group B exhibited superior improvement, with mean YBT scores increasing from 77.40 ± 6.68 at baseline to 90.87 ± 5.25 at week 12, representing a 13.47% gain, compared to Group A's improvement from 74.33 ± 4.34 to 83.67 ± 3.68 (+9.34%).

The enhanced performance in Group B is attributed to the synergistic physiological adaptations resulting from plyometric training and BFRT. Plyometrics improved neuromuscular coordination, reflex stabilization, and proprioceptive acuity, as supported by Myer et al. (2006)[36] and Hewett et al. (2005)[37], while BFRT promoted muscle hypertrophy and strength even at low intensities, making it especially beneficial in early rehab stages (Takarada et al., 2000; Ohta et al., 2003)[38-39]. Additionally, exercises such as single-leg squats and BOSU ball training enhanced limb proprioception and joint control.

While some literature (Centner et al., 2019; Rogan et al., 2017)[40] suggests variability in BFRT effectiveness for balance, and others (Paterno et al., 2010)[41] caution against early plyometric loading post-ACLR, the present study showed no adverse effects like graft failure or increased laxity, indicating appropriate protocol timing and progression. The statistically significant difference in Group B ($p<0.01$) further confirms the efficacy of this multimodal training approach in enhancing dynamic stability, with a 3.6% superior improvement over the conventional group. The findings validate that integrating plyometric and BFRT into post-ACLR rehabilitation significantly accelerates dynamic stability recovery, as measured by YBT. This approach may serve as a valuable adjunct to conventional rehab, especially during early return-to-sport phases, ensuring safer and faster functional reintegration.

The International Knee Documentation Committee (IKDC) subjective knee form is a widely accepted outcome measure used to assess symptoms, function, and sports activity in patients with various knee pathologies, including those who have undergone anterior cruciate ligament reconstruction (ACLR). It reflects the patient's perceived recovery status and provides a standardized method for assessing functional limitations. In the present study, IKDC scores were used to evaluate improvements in self-reported knee function over a 12-week rehabilitation period in both groups: Group A (Conventional Rehabilitation) and Group B (experimental group).

Group A participants followed a structured, progressive rehabilitation protocol focusing on restoring range of motion, reducing pain and swelling, strengthening the quadriceps/hamstring muscles for optimal force production, and improving proprioception. The mean (± SD) of IKDC score improved from 66.20 ± 6.72 at baseline to 73.53 ± 4.44 at 6 weeks, and further to 80.93 ± 3.90 at 12 weeks, reflecting a 14.73% improvement over the 12-week intervention period. These improvements align with previous studies indicating that conventional physiotherapy can significantly enhance self-reported knee function following ACLR. However, conventional rehabilitation may lack the stimulus required for rapid hypertrophy and high-speed neuromuscular adaptations, particularly in the early and intermediate stages. Ardern et al. (2014)[42] emphasized that while patients may report satisfactory improvements in symptoms and basic function, they often experience residual deficits in confidence and readiness for high-level activities. This may explain why Group A, despite showing statistically significant improvements, had lower final IKDC scores compared to Group B (experimental group).

Group B (experimental group) n=15, participants received a combined intervention consisting of plyometric training and blood flow restriction training (BFRT) integrated with Russian stimulation. The mean (± SD) of IKDC scores in this group improved from (67.13 ± 6.14) at baseline to (79.67 ± 6.77) at 6 weeks, and to (89.67 ± 4.40) at 12 weeks, showing a total gain of 22.53%. This significantly shows greater improvement which may be attributed by the dual benefits of the interventions. Plyometric training improves the efficiency of the neuromuscular system by enhancing rate of force development (RFD) and limb coordination. BFRT complements these outcomes by inducing early strength gains and muscle hypertrophy, particularly in the quadriceps, which are essential for knee function. Furthermore, Devana et al. (2024)[43] demonstrated that NCAA athletes undergoing ACLR rehabilitation with BFRT showed faster improvements in subjective and objective measures of knee function, including IKDC, compared to those undergoing conventional rehabilitation.

However, certain authors have raised concerns regarding these interventions. Willy et al. (2016)[44] argued that aggressive rehabilitation may compromise graft healing if introduced prematurely. Similarly, Harner et al. (2001)[45] emphasized that excessive mechanical stress during the revascularization phase (6–12 weeks post-op) may lead to graft failure. This underscores the importance of carefully planned and gradually progressed protocols. Another limitation highlighted by Centner et al. (2019)[40] is the inconsistency of BFRT effects on subjective outcomes like IKDC, particularly when the training is not individualized or lacks sufficient intensity. However, the present study incorporated personalized load adjustment and close monitoring, likely contributing to the more favorable outcomes observed.

By week 12, Group B (experimental group) achieved a mean (± SD) of IKDC score of (89.67 ± 4.40), compared to 80.93 ± 3.90 in Group A. This difference of 8.74 points was both statistically significant ($p < 0.01$) and clinically meaningful, as previous research has identified a minimum clinically important difference (MCID) for IKDC scores to be approximately 6–9 points (Irrgang et al., 2006). Thus, the superior improvement in Group B (experimental group) not only surpasses the MCID but also approaches normative values for uninjured athletic populations, indicating near-complete functional restoration. In conclusion, both rehabilitation approaches produced significant improvements in IKDC scores over the 12-week period. However, the combined intervention in Group B (experimental group) was significantly more effective, producing faster and more substantial gains in self-reported knee function. This enhancement is likely due to the synergistic effects of plyometric training and BFRT in promoting neuromuscular re-education, muscle hypertrophy, and confidence in functional tasks.

LIMITATIONS AND FUTURE SCOPE:

The present study, while yielding significant findings through Y-Balance Test (YBT) and IKDC, faced limitations such as a short study duration, small sample size, and lack of isokinetic strength testing, which may affect the generalizability and objectivity of results. Convenience sampling and absence of participant stratification by sport level introduced selection bias. Additionally, limited geographical scope and no long-term follow-up restricted broader applicability and prevented assessment of sustained outcomes. Future studies should incorporate larger, randomized samples, objective strength assessments, longer follow-up, and additional tools like the Landing Error Scoring System to provide a more comprehensive evaluation of return-to-sport readiness and long-term functional recovery.

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Appendix 1

Exercise Protocol for Group A

1st – 4th week	**5th- 8th week**	**9th – 12th week**
Wobble board balancing	Captain Morgan	Single leg perturbations on BOSU ball
Double leg squat On BOSU ball(quads)	Star excursion	Nordic hamstrings with weight
Lateral band stepping ;monster walk (for glutes)	Side plank on swiss ball	45-degree cutting and spinning drill(agility)
Single leg skaters squat 3 way (glutes)	Around the clock with swiss ball (core)	Multidirectional shuttle(agility)
Forward lunges(quads)	Reverse Nordic hamstring curls (quads)	Figure of eight run(agility)
Knee extension(weighted machine)	Reverse Nordic hamstring curls (quads)	Swiss ball Prone jackknife (core)
Bilateral shuttle run (agility)	Carioca/grapevine stepping(agility)	Single leg stair jumps
Side shuffle/ side stepping (agility)	Side stepping cutting(agility)	Single leg drop vertical jump
Forward lunge, with overhead swiss ball (core)	Single leg squat on BOSU ball	Single leg hurdle jump
Bird dog (core)	Split squat	Single leg medial drop landing
Nordic hamstring curls	Bounding in place	Weighted Bulgarian squats (quads)
Broad jump for distance	Single leg drop jump	Weighted Sumo squat
Tuck jumps	180 degrees jump	-
Cone jumps/barrier jumps	-	-

Progression Criteria

Progression criteria to progress for 5th week	1. Able to do treadmill walk × 20 minutes 2. Anterior Y Balance within 4cm 3. Pass double leg hop 4. Pass double leg drop box
Progression criteria to progress for 9th week	1. Pass single leg drop box test 2. Pass single leg hop 3. able to run × 20 minutes 4. Closed chain strength > 1.5(males) and 1.0(females) 5. times body mass(8RM)

Appendix 2

Exercise Protocol for Group B

1st – 4th week	**5th- 8th week**	**9th – 12th week**
Bilateral squat jump (in place, forward)	Bilateral counter movement jump to unilateral landing	Single leg squat jump
bilateral jump on trampoline	Vertical stop jump	Single-leg medial drop landing
Bilateral drop jump (16 inches box)	Split jump	Unilateral land and jump
Landing and jump	Tuck jump	Lateral hop (medicine ball)
Step up jump (alternating)	Weighted squat jump	Single leg hurdle jump with weight
Bilateral squat on wobble board with weight	Step cut at various angles 30,45,60,90 degrees	Step cut with perturbations (medicine ball)
180 degrees jump	Hop singular (in place/forward/lateral)	Multidirectional shuttle run
Lunge push back	Unilateral hurdle jump	Figure of eight run
Lunge impact	Lateral Single leg drop jump	Single leg up down task
-	Advanced bounding (alternate leg split jump in front)	On field change of direction with perturbations
-	-	180 degree single leg jump

Progression Criteria

Progression criteria to progress 5th week	1. Good bilateral drop jump mechanics 2. Good single leg landing control 3. Lunges and squat strength > 1.5 times body mass(8RM)
Progression criteria to progress 9th week	1. Isokinetic Leg symmetry index>90% 2. Unilateral landing 3. unilateral drop jump 4. Change of direction mechanics 5. on field Closed chain strength > 1.5(males)and 1.0(females) times body mass(8RM)