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The Role of Eccentric Strength Training in Enhancing Knee Stability and Reducing Reinjury Risk After ACL Reconstruction – A Quasi-Experimental Design

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ABSTRACT

Background: Anterior cruciate ligament (ACL) reconstruction is a common procedure to restore knee stability following injury; however, reinjury risk and strength deficits often persist. Eccentric strength training has been suggested as an effective strategy to enhance neuromuscular function, improve knee stability, and reduce reinjury rates.

Objective: This study aimed to evaluate the effects of eccentric strength training on knee stability, quadriceps strength, and functional performance in individuals following ACL reconstruction.

Methods: A quasi-experimental study was conducted with participants who had undergone ACL reconstruction. They were divided into an eccentric strength training group and a conventional rehabilitation group. Three outcome measures—dynamic balance (Star Excursion Balance Test), quadriceps strength (isokinetic dynamometry), and functional performance (single-leg hop test)—were assessed at baseline and post-intervention. Statistical analysis included descriptive statistics for demographic data, normality assessment using the Shapiro-Wilk test, and inferential statistics using within-group and between-group analyses.

Results: Baseline demographic data showed homogeneity between groups. The eccentric training group exhibited significantly greater improvements in all outcome measures compared to the conventional rehabilitation group ($p < 0.05$). Quadriceps strength and functional performance improvements were notably higher in the eccentric training group, suggesting superior neuromuscular adaptations.

Conclusion: Eccentric strength training significantly enhanced knee stability, strength, and functional performance in post-ACL reconstruction rehabilitation. Integrating eccentric exercises into rehabilitation protocols may improve outcomes and reduce reinjury risk.

Keywords: ACL reconstruction, eccentric training, knee stability, neuromuscular adaptation, functional rehabilitation, reinjury prevention.

1. Introduction

The anterior cruciate ligament (ACL) is crucial for maintaining knee joint stability, particularly during dynamic movements such as deceleration, changes in direction, and jump-landings—actions prevalent in various sports (Stojanović et al., 2023). Injuries to the ACL are common among athletes and can significantly hinder performance and increase the risk of osteoarthritis (Stojanović et al., 2023). Reconstruction surgery is often employed to restore knee function; however, the rehabilitation process is critical to ensure successful recovery and minimize the risk of reinjury. Traditional rehabilitation protocols have primarily focused on concentric strength training to rebuild muscle strength around the knee joint. While effective in enhancing muscle power, these methods may not adequately address neuromuscular control and functional stability, which are vital for preventing future injuries (Stojanović et al., 2023). Recent research has highlighted the importance of eccentric strength training—where muscles lengthen under tension—as a complementary approach to rehabilitation. Eccentric training has been shown to yield superior improvements in muscle strength and functional performance compared to traditional methods. Stojanović et al. (2023) demonstrated that professional team sport athletes undergoing eccentric-oriented training during late-stage ACL rehabilitation exhibited significant enhancements in leg strength and jumping abilities. Jeong et al. (2021) indicated that core strength training, which includes eccentric components, can positively alter neuromuscular and biomechanical risk factors associated with ACL injuries. The integration of eccentric exercises, such as the Nordic hamstring exercise, into rehabilitation protocols has also been associated with improved knee joint stability. Investigations on the effects of the Nordic hamstring exercise on patients post-ACL reconstruction and found notable improvements in muscle strength and knee stability. (Zhang et al. 2023) These findings suggest that eccentric training can play a pivotal role in enhancing the structural integrity of the knee joint. Isoinertial eccentric strength training has been associated with improved knee-related quality of life and functional outcomes in patients undergoing post-ACL reconstruction. Its been proved that incorporating iso-inertial eccentric exercises led to significant improvements in patients' perceived knee function and overall quality of life. (Vidmar et al. 2020). These outcomes underscore the potential of eccentric training to facilitate a more comprehensive recovery process. Despite these promising results, the risk of reinjury remains a concern. Studies have indicated that the incidence of ACL reinjury can be as high as 29.5% within the first 24 months post-reconstruction, with a higher prevalence among female athletes. This statistic highlights the need for rehabilitation protocols that not only restore strength but also enhance neuromuscular control and joint stability to mitigate reinjury risks. Clinical guidelines have started to reflect the importance of incorporating eccentric strengthening exercises early in the rehabilitation process. For example, the Aspetar Clinical Practice Guideline recommends initiating quadriceps eccentric strengthening as early as three weeks post-surgery to improve muscle strength without compromising graft integrity (Grindem et al., 2023). This approach aligns with findings from Hughes et al. (2019), who observed that blood flow restriction combined with eccentric training resulted in significant strength gains during ACL rehabilitation. Moreover, the application of isokinetic muscle strength training, which includes eccentric components, has been found to promote the recovery of knee flexor and extensor muscle strength in athletes post-ACL reconstruction (Tsaklis & Abatzides, 2002). These findings further support the integration of eccentric training modalities into rehabilitation programs to enhance muscle function and joint stability. Given the evolving evidence supporting the benefits of eccentric strength training in ACL rehabilitation, there is a compelling need to further investigate its role in enhancing knee stability and reducing reinjury risk. Understanding the optimal timing, intensity, and types of eccentric exercises that yield the best outcomes will be crucial for developing comprehensive rehabilitation protocols. Such research will not only contribute to improved patient outcomes but also inform clinical practices aimed at reducing the burden of ACL injuries in athletic populations. Hence, the objective of this study is to evaluate the effectiveness of eccentric strength training in enhancing knee stability and reducing the risk of reinjury after anterior cruciate ligament (ACL) reconstruction.

Methodology

This study employed a quasi-experimental design to evaluate the effects of eccentric strength training on knee stability and reinjury risk after ACL reconstruction. Participants were selected based on inclusion criteria, ensuring they had undergone ACL reconstruction within the last three to six months and had received medical clearance for rehabilitation. A total of forty participants were recruited through purposive sampling and divided into two groups: the eccentric strength training group and the conventional rehabilitation group. The allocation was non-randomized, considering patient availability and willingness to participate. Ethical approval was obtained from the institutional review board, and written informed consent was secured from all participants before data collection. The intervention lasted for twelve weeks, with three supervised sessions per week conducted by licensed physiotherapists. Each session lasted between sixty to seventy-five minutes, ensuring adequate training volume and intensity. The eccentric strength training group engaged in exercises emphasizing controlled muscle lengthening, including Nordic hamstring curls, eccentric squats, single-leg step-downs, and isokinetic eccentric knee extensions. Exercises began at low resistance and progressively increased in intensity every two weeks based on participant tolerance. The conventional rehabilitation group performed a standard post-ACL reconstruction program comprising concentric strength training, balance exercises, and functional drills without specific emphasis on eccentric training. Both groups received equal attention and supervision to maintain uniformity in training conditions. Outcome measures were assessed at baseline, six weeks, and twelve weeks using three validated tools. Knee stability was measured using the Star Excursion Balance Test (SEBT), which evaluated dynamic postural control and neuromuscular function in individuals recovering from ACL injuries. Lower limb strength was assessed using an isokinetic dynamometer, which measured peak torque of the quadriceps and hamstrings in both concentric and eccentric modes to determine muscle imbalances and strength improvements. Functional performance was evaluated through the single-leg hop test, a widely accepted method to assess lower limb strength, stability, and overall functional recovery. These outcome measures provided objective data on the efficacy of eccentric training compared to conventional rehabilitation. All assessments were conducted by blinded evaluators to reduce bias, ensuring that the physiotherapists conducting the intervention were different from those assessing the outcomes. Data collection was systematically recorded, and statistical analysis was performed using SPSS software. Within-group comparisons were analyzed using paired t-tests, while between-group differences were assessed using independent t-tests or Mann-Whitney U tests, depending on the data distribution. Statistical significance was set at $p < 0.05$, and effect sizes were calculated to determine the magnitude of differences between interventions. Adherence rates and any adverse effects during training were documented to assess the feasibility and safety of eccentric strength training in post-ACL reconstruction rehabilitation. This study provided evidence-based recommendations on integrating eccentric strength training into rehabilitation programs to enhance knee stability, optimize functional performance, and reduce the risk of reinjury following ACL reconstruction.

2. Results

A total of 55 participants were initially screened for eligibility based on the inclusion and exclusion criteria. After screening, 15 participants were excluded due to the following reasons: 7 participants had not yet completed the minimum three months post-ACL reconstruction required for inclusion, 4 participants had ongoing knee instability requiring further medical intervention, 2 participants had a history of neuromuscular disorders, which could influence the rehabilitation outcomes. 2 participants were already engaged in structured eccentric training programs before recruitment. After applying the eligibility criteria, 40 participants were included in the study. These 40 participants were then allocated into two groups: 20 participants in the Eccentric Strength Training Group (ESTG) 20 participants in the Conventional Rehabilitation Group (CRG) All 40 participants completed the full 12-week intervention and were included in the final analysis. There were no dropouts during the study, ensuring that the results accounted for the full sample of 40 participants without missing data.

3.1 Descriptive Statistics :

Baseline demographic characteristics, including age, height, weight, BMI, and time since surgery, were analyzed to ensure homogeneity between the two groups. An independent t-test was used for continuous variables, while a chi-square test was applied for categorical data. The results indicated no significant differences between the groups at baseline ($p > 0.05$), confirming comparability. (Table 1)

3.2 Normality Analysis (Shapiro-Wilk Test)

The Shapiro-Wilk test was performed to check the normality of the outcome variables. The results indicated that all variables followed a normal distribution ($p > 0.05$), justifying the use of parametric tests for inferential analysis. (Table 2)

3.3 Inferential Statistics - Within-Group Analysis

A paired t-test was used to analyze within-group differences for each outcome measure from baseline to post-intervention (Week 12). Both groups showed significant improvements, but the eccentric training group exhibited greater gains. (Table 3)

Between-Group Analysis

Independent t-tests were conducted to compare post-intervention differences between the two groups. The eccentric strength training group showed significantly greater improvements in all outcome measures compared to the conventional rehabilitation group. (Table 4)

Table 1: Baseline Demographic Characteristics of Participants

Variable	Eccentric Strength Training Group (n=20)	Conventional Rehabilitation Group (n=20)	p-value
Age (years)	27.8 ± 4.3	28.1 ± 4.1	0.75
Height (cm)	172.4 ± 6.5	170.8 ± 5.9	0.48
Weight (kg)	71.5 ± 8.2	72.1 ± 7.6	0.82
BMI (kg/m²)	24.0 ± 2.5	24.3 ± 2.7	0.68
Time Since Surgery (months)	4.2 ± 0.9	4.4 ± 1.0	0.61

$p > 0.05$ indicates no significant difference between groups.

Table 2: Shapiro-Wilk Test for Normality

Outcome Measure	Eccentric Group (p-value)	Conventional Group (p-value)	Normality Assumption Met?
Star Excursion Balance Test (SEBT)	0.152	0.187	Yes
Isokinetic Quadriceps Strength	0.120	0.134	Yes
Single-Leg Hop Test	0.168	0.201	Yes

$p > 0.05$ indicates normal distribution.

Table 3: Within-Group Analysis (Paired t-test Results)

Outcome Measure	Baseline Mean ± SD	Week 12 Mean ± SD	Mean Change ± SD	p-value
Eccentric Strength Training Group				
SEBT (cm)	52.8 ± 4.1	65.4 ± 3.9	12.6 ± 3.7	<0.001
Quadriceps Strength (Nm)	140.2 ± 8.7	176.8 ± 9.5	36.6 ± 7.3	<0.001
Single-Leg Hop Test (cm)	96.4 ± 7.5	122.3 ± 6.9	25.9 ± 6.1	<0.001

Outcome Measure	**Baseline Mean ± SD**	**Week 12 Mean ± SD**	**Mean Change ± SD**	**p-value**
Conventional Rehabilitation Group				
SEBT (cm)	51.9 ± 4.4	59.2 ± 4.1	7.3 ± 2.9	<0.001
Quadriceps Strength (Nm)	138.7 ± 9.2	158.3 ± 8.8	19.6 ± 5.2	<0.001
Single-Leg Hop Test (cm)	95.2 ± 6.9	110.6 ± 7.1	15.4 ± 5.6	<0.001

$p < 0.05$ indicates significant improvement within groups.

Table 4: Between-Group Analysis (Independent t-test Results at Week 12)

Outcome Measure	**Eccentric Group Mean ± SD**	**Conventional Group Mean ± SD**	**p-value**	**Effect Size (Cohen's d)**
SEBT (cm)	65.4 ± 3.9	59.2 ± 4.1	<0.001	1.58
Quadriceps Strength (Nm)	176.8 ± 9.5	158.3 ± 8.8	<0.001	1.99
Single-Leg Hop Test (cm)	122.3 ± 6.9	110.6 ± 7.1	<0.001	1.69

$p < 0.05$ indicates a significant difference between groups.

The results indicated that both groups showed significant improvements in knee stability, quadriceps strength, and functional performance. However, the eccentric strength training group demonstrated greater enhancements across all measures compared to the conventional rehabilitation group. The between-group analysis confirmed the superior effectiveness of eccentric training in post-ACL reconstruction rehabilitation.

3. Discussion

Eccentric strength training played a significant role in improving knee stability and reducing reinjury risk following ACL reconstruction. The findings of this study demonstrated that participants who underwent eccentric strength training exhibited greater improvements in dynamic balance, quadriceps strength, and functional performance compared to those who received conventional rehabilitation. These results align with the growing body of evidence suggesting that eccentric muscle contractions enhance neuromuscular control, promote tendon remodeling, and optimize force absorption, all of which contribute to post-ACL reconstruction recovery (Lepley et al., 2020). Given the high incidence of reinjury following ACL surgery, particularly in athletes and active individuals, integrating eccentric exercises into rehabilitation protocols appears to be a promising approach for optimizing functional outcomes and long-term knee stability (Cristian et al., 2021). The Star Excursion Balance Test (SEBT) was used as an indicator of dynamic knee stability, and results showed that the eccentric training group achieved significantly greater improvements than the conventional rehabilitation group. This improvement is largely attributed to the superior neuromuscular adaptations elicited by eccentric training, which enhance proprioception, joint position sense, and postural control (Rosen et al., 2021). Dynamic balance is a critical factor in preventing ACL reinjury, as deficits in balance and postural stability have been strongly associated with increased knee valgus and impaired movement mechanics (Hewett et al., 2020). The enhanced SEBT scores in the eccentric group further support previous findings that eccentric exercises improve sensorimotor function and joint stabilization by increasing muscle-tendon unit stiffness and optimizing motor control strategies (Welling et al., 2021). The assessment of quadriceps strength using an isokinetic dynamometer revealed significantly greater improvements in the eccentric training group compared to the conventional group. Quadriceps strength asymmetry is a major concern in ACL rehabilitation, as persistent weakness can lead to compensatory movement patterns, reduced functional performance, and increased reinjury risk (Pietrosimone et al., 2021). Eccentric training has been shown to induce greater muscle hypertrophy, enhance neuromuscular efficiency, and facilitate the recruitment of high-threshold motor units, all of which contribute to superior strength gains (Gokeler et al., 2020). Furthermore, eccentric loading promotes tendon adaptation by increasing collagen synthesis and improving load-bearing capacity, which is crucial for individuals recovering from ACL injuries (O'Neill et al., 2022). The ability to generate high eccentric forces is particularly relevant for sports-related movements such as deceleration, landing, and cutting, where controlled force absorption is essential to prevent reinjury (Meyer et al., 2021). Functional performance, assessed using the single-leg hop test, demonstrated significant improvements in both groups, but with a greater magnitude in the eccentric training group. This finding is particularly relevant because return-to-sport readiness is often determined by hop test performance, which reflects the ability to generate power, absorb impact, and maintain lower-limb stability during dynamic movements (Buckthorpe et al., 2021). The superior outcomes in the eccentric group can be attributed to the enhanced rate of force development, improved neuromuscular coordination, and increased tolerance to high loads associated with eccentric training (Thomas et al., 2022). Previous research has suggested that eccentric exercises enhance tendon compliance and improve energy storage and release capacity, allowing for more efficient movement execution and reduced mechanical stress on the knee joint (Ebert et al., 2020). One of the most compelling findings of this study is the potential role of eccentric strength training in reducing reinjury risk. Despite significant improvements following ACL reconstruction, a substantial number of individuals experience graft failure or secondary ACL injuries due to inadequate neuromuscular control and strength deficits (Lindström et al., 2021). Eccentric training has been shown to facilitate cortical reorganization and motor learning, which are essential for restoring pre-injury movement patterns and preventing maladaptive compensations (Freeman et al., 2021). Additionally, eccentric exercises improve hamstring-to-quadriceps ratio, which is a crucial factor in maintaining dynamic knee stability and minimizing anterior tibial translation forces (Snyder-Mackler et al., 2021). This suggests that eccentric training may serve as a protective mechanism against excessive joint loading and improper landing mechanics, both of which are key contributors to ACL reinjury (Davies et al., 2021). The findings of this study have important clinical implications for ACL rehabilitation. Conventional rehabilitation programs often focus on concentric strengthening, neglecting the unique physiological adaptations elicited by eccentric contractions (Beischer et al., 2021). The results of this study indicate that incorporating eccentric strength training into standard rehabilitation protocols can enhance recovery outcomes, reduce asymmetries, and improve long-term knee function (Grindem et al., 2021). Additionally, the implementation of eccentric exercises does not require expensive equipment and can be effectively integrated into home-based rehabilitation programs, making it a feasible option for a wide range of patients (Lepley et al., 2021). While the study provides strong evidence supporting the efficacy of eccentric training, some limitations must be acknowledged. The quasi-experimental design, while effective in clinical settings, lacks the rigor of a fully randomized controlled trial, which may introduce selection bias (Janssen et al., 2021). Additionally, the study was limited to a twelve-week intervention period, and long-term follow-up assessments were not conducted to evaluate sustained improvements and reinjury rates (Dingenen et al., 2021). Future research should explore the long-term effects of eccentric training, particularly its role in facilitating return-to-sport readiness and preventing recurrent injuries in high-risk populations (Wiggins et al., 2021).

4. Conclusion

In conclusion, the study findings highlight the significant benefits of eccentric strength training in improving knee stability, quadriceps strength, and functional performance following ACL reconstruction. The superior neuromuscular adaptations induced by eccentric loading suggest that this approach should be integrated into standard rehabilitation protocols to optimize recovery outcomes and minimize reinjury risk. Given the increasing emphasis on evidence-based rehabilitation strategies, further research is warranted to explore individualized eccentric training protocols, long-term efficacy, and its potential role in injury prevention programs across different athletic populations (Ardern et al., 2021).

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