

Dose–Response Relationship Between Backward Treadmill Inclination and Quadriceps Strength Recovery After Anterior Cruciate Ligament Reconstruction: A Randomized Controlled Trial

Diker Dev Joshi¹, Dr. Vikram Shetty^{2*}, Dr. Dhanesh Kumar KU³, Dr. Pravin Aaron⁴

¹PhD Scholar, Nitte Institute of Physiotherapy, Nitte (Deemed to be University) Mangalore, Email: diker.20phdpt202@student.nitte.edu.in, orcid id:0000-0003-2931-863X

^{2*}Professor, Orthopedics, Nitte (Deemed to be University) Mangalore, Email: docvickys@nitte.edu.in , orcid id:0009-0009-9800-0036 ³Principal, Nitte Institute of Physiotherapy, Nitte (Deemed to be University), Mangalore, Email: principal.nipt@nitte.edu.in , orcid id:0000-0001-9200-521X

⁴Professor, Cardiorespiratory Physiotherapy, RGUHS, Bangalore, Email: pipprincipal@gmail.com , orcid id:0009-0001-8363-5532

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ABSTRACT:

Background

Quadriceps weakness is one of the most common impairments following anterior cruciate ligament (ACL) reconstruction and may delay functional recovery and return to activity. Backward treadmill walking has been suggested as an effective rehabilitation strategy to improve quadriceps strength; however, the dose–response relationship between treadmill inclination and strength recovery remains unclear.

Objective

To investigate the dose–response relationship between graded backward treadmill inclination and quadriceps strength recovery following ACL reconstruction.

Methodology

This Randomized Controlled Trial (RCT) included 60 participants who had undergone ACL reconstruction and were randomly allocated into five groups (n=12 each). Groups A, B, C and D performed backward treadmill walking at 0°, 5°, 10° and 15° inclination respectively, while Group E received conventional rehabilitation. Training was performed for 20 minutes, three times per week for four weeks. Quadriceps strength was measured using a handheld dynamometer at baseline and weekly for four weeks. Comparisons The Friedman test was employed for within-group analyses, or the Friedman test was used for among-group assessments the Kruskal–Wallis test.

COPYRIGHT STATEMENT: Copyright: © 2026 Authors. Open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).	Results All groups demonstrated progressive improvements in quadriceps strength over the four-week intervention period. Within-group analysis showed statistically significant improvements in strength in all groups ($p < 0.001$). Among-group comparisons showed no statistically substantial differences at baseline or at weekly follow-ups ($p > 0.05$). However, although descriptive trends in strength progression were observed across groups, no statistically substantial differences were found among the intervention groups. Conclusion Graded backward treadmill training was associated with improvements in quadriceps strength across all groups following ACL reconstruction. However, no statistically substantial differences were observed among groups. While descriptive trends were noted, a definitive dose–response relationship could not be established. Keywords: ACL reconstruction, Backward treadmill walking, Quadriceps strength, Dose–response relationship, Rehabilitation, Randomized controlled trial
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Introduction

Anterior cruciate ligament (ACL) injury is one of the most common knee injuries among physically active individuals and frequently requires surgical reconstruction to restore joint stability and function [1,2]. In spite of the improvement in the surgical methods and rehabilitation procedures, the quadriceps weakness continues to be one of the most debilitating issues of ACL reconstruction [3,4]. The deficits in the quadriceps strength persist several months post-surgery and are linked with poor performance in functional terms, altered knee biomechanics, later returns to sport and higher re-injury rates [5-7].

Quadriceps strength restoration is thus regarded as a major objective of post-surgical ACL rehabilitation. Stability of the knee joints, shock absorption and safe recovery to functional activities depends on adequate strength of the quadriceps [8,9]. Nevertheless, muscle strength restoration after ACL reconstruction is usually affected by patient factors that include arthrogenic muscle inhibition, decreased

voluntary activation, pain, joint effusion, and inadequate mechanical loading during the rehabilitation process [10,11]. This is why it is still a clinical priority to determine rehabilitation strategies that would be safe in improving the quadriceps strength recovery.

Closed kinetic chain exercises have gained widespread approvals in the rehabilitation of ACL because they have functional relevance with decreased anterior tibial shear forces [12,13]. Backward walking is one of these interventions that have received interest as an effective rehabilitation measure due to its potential in raising the level of quadriceps muscle activity and decreasing the patellofemoral joint stress [14–16]. Compared to forward walking, backward walking also involves more neuromuscular coordination and proprioceptive control and this could be another factor in better muscle performance [17,18].

It is also possible that treadmill inclination has additional effects on mechanical and neuromuscular requirements of walking

backwards. Raising treadmill inclinations elevates muscular workload, metabolic demand and joint loading, which could ultimately cause strength adaptation [19,20]. One of the key concepts of rehabilitation is progressive loading, and graded incline walking can be one of the convenient ways of delivering controlled mechanical overload during ACL rehabilitation [21]. Nevertheless, it is not clear what the best angle is that would be used to achieve maximum strength recovery and safety.

Despite the fact that past studies have shown an enhancement in the quadriceps with regards to using backward walking due to treadmill inclination interventions, little Studies have been carried out to determine the dose-response relationship among treadmill inclination and strength recovery after ACL reconstruction. The effect of varying training intensities on the recovery rate and magnitude of strength can assist clinicians to develop a more efficient rehabilitation regimen.

Thus, this research paper was intended to examine the dose-response of graded backward treadmill inclination to quadriceps strength recovery after ACL reconstruction. The hypothesis was that the greater the treadmill inclination, the greater the increase in quadriceps strength as a result of the mechanism demand and the neuromuscular response.

Methodology

The design of this investigation was a randomized controlled experiment to investigate the dose-response relationship between graded backward treadmill inclination and quadriceps strength recovery after reconstructing the anterior cruciate ligament (ACL). The study was conducted in hospitals affiliated with the Department of Physiotherapy following permission from the Institutional Ethics Committee (Ref No: NU/CEC/2023/359). The Rules of Helsinki was followed in conducting the study. Before taking part, each subject gave written informed consent. This manuscript represents a secondary analysis of strength recovery data

obtained from the randomized controlled trial, while other outcomes from the trial have been reported separately to address different research objectives [22].

Total 60 participants who had experienced arthroscopic ACL reconstruction using a semitendinosus graft were recruited for the study. Participants aged between 18 and 45 years, who were between 3 and 6 months post-surgery, able to walk independently without assistive devices, and having knee range of motion between 0° and 110° were included in the study. Participants with revision ACL reconstruction, associated ligament injuries, inflammatory joint diseases, neurological disorders, recent fractures, or any other musculoskeletal conditions affecting gait were excluded from the study. These eligibility criteria were selected based on commonly used standards in ACL rehabilitation trials [23,24].

Participants were divided at random between five groups (n = 12 per group) utilizing a randomization sequence produced by a computer. An independent researcher constructed opaque, sealed envelopes with sequential numbers to ensure allocation concealment. Randomization procedures similar to this have been widely used in clinical rehabilitation trials to minimize selection bias. [25] Because of the nature of the treatment, it was not possible to blind participants and therapists. To minimize measurement bias, all outcome assessments were performed using standardized testing procedures, and participants were provided consistent instructions during strength testing. Group A performed backward treadmill walking at 0° inclination, Group B at 5° inclination, Group C at 10° inclination, and Group D at 15° inclination, while Group E received conventional rehabilitation exercises and served as the control group.

The intervention procedure was the backward treadmill walking with a fixed speed of 1.3 km/hour. Each training session was 20 minutes and was conducted three times a week which adds up to four weeks. All participants also

continued their conventional rehabilitation program consisting of range of motion exercises, quadriceps strengthening exercises, and functional training as prescribed in standard ACL rehabilitation protocols [26,27].

Quadriceps strength was considered the primary outcome measure and was measured by using a handheld dynamometer. Strength assessment was carried out with the subject in a typical seated position with their legs and hips bent to a 90-degree. Participants were instructed to perform maximal voluntary isometric contraction of the quadriceps against the dynamometer. Three trials were recorded and the highest value was considered for analysis. Handheld dynamometry is considered a reliable and valid method for assessing quadriceps strength in clinical populations [28,29]. Strength measurements were recorded at baseline and at weekly intervals for four weeks to determine the rate of strength recovery.

Statistical analysis was performed using SPSS version 21. Descriptive statistics were used to review demographic variables. For within-group comparisons, the Friedman test was employed, and for between-group assessments, the Kruskal–Wallis test. The level of statistical significance was set at $p < 0.05$ [30,31]. In addition, effect sizes and 95% confidence intervals were considered to evaluate the magnitude and precision of observed differences. These estimates should be interpreted with caution due to the relatively small sample size.

All participants completed the study protocol and no dropouts were reported during the intervention period.

Participant flow through the study is presented in the CONSORT diagram (Figure 1).

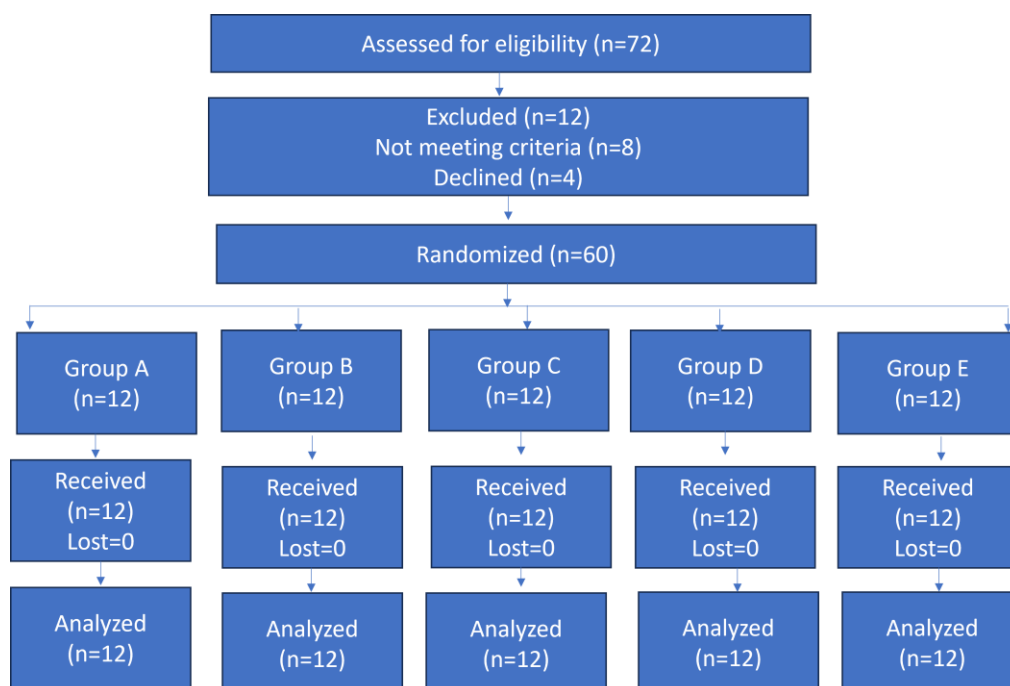


Figure 1: CONSORT Flow Diagram for recruiting, assigning, monitoring, and analyzing participants

Results

Overall 60 participants were randomized and enrolled in the study into five groups with 12 participants in all group. All participants

completed the four-week intervention period and no dropouts or adverse events were reported. Baseline demographic characteristics including age, weight, height, BMI, gender distribution and side affected were comparable

across the five groups, indicating homogeneity of the sample and successful randomization (Table 1).

Table 1: Description of background variables of subjects with anterior cruciate ligament reconstruction

S.No .	Background Variable	Group A (n=12)	Group B (n=12)	Group C (n=12)	Group D (n=12)	Group E (n=12)	Statistica l Test
		Range / Mean±SD	Range / Mean±SD	Range / Mean±SD	Range / Mean±SD	Range / Mean±SD	
1	Age (years)	18–44 / 31.25±9.60	18–38 / 29.75±6.50	22–45 / 34.75±8.85	20–45 / 33.00±7.75	19–45 / 31.50±8.68	F=0.621, p=0.649, NS
2	Weight (kg)	46–67 / 57.77±6.24	45–79 / 62.98±10.48	48–69 / 61.74±5.91	51–92 / 66.77±10.03	52–90 / 62.67±9.84	F=1.631, p=0.180, NS
3	Height (m)	1.49–1.69 / 1.61±0.06	1.54–1.75 / 1.66±0.07	1.57–1.71 / 1.65±0.05	1.55–1.72 / 1.65±0.06	1.57–1.67 / 1.63±0.04	F=1.261, p=0.296, NS
4	BMI	19.38–25.85 / 22.24±2.20	18.49–26.89 / 22.84±2.71	17.83–26.62 / 22.82±2.50	21.23–31.10 / 24.55±2.47	20.57–32.27 / 23.66±3.18	F=1.383, p=0.243, NS
5	Gender (Male/Female)	6 (50%) / 6 (50%)	11 (91.7%) / 1 (8.3%)	11 (91.7%) / 1 (8.3%)	9 (75%) / 3 (25%)	9 (75%) / 3 (25%)	$\chi^2=7.826$, df=4, p=0.098, NS
6	Side affected (Left/Right)	6 (50%) / 6 (50%)	7 (58.3%) / 5 (41.7%)	5 (41.7%) / 7 (58.3%)	6 (50%) / 6 (50%)	4 (33.3%) / 8 (66.7%)	$\chi^2=1.741$, df=4, p=0.783, NS

Quadriceps Strength Recovery

The Friedman test was used for within-group assessments, while between-group assessments were carried out using the Kruskal-Wallis test. The statistical threshold was $p < 0.05$. Table 2

presents the weekly progression of quadriceps strength among the five groups following graded backward treadmill rehabilitation. All groups showed a steady rise of mean quadriceps strength during week-0 to week-4.

Table 2: Quadriceps strength (N) changes with weekly progress of the program of graded back treadmill rehabilitation

Group	Pre (Mean±SD)	Week-1 (Mean±SD)	Week-2 (Mean±SD)	Week-3 (Mean±SD)	Week-4 (Mean±SD)
Group A	5.25 ± 1.13	5.38 ± 1.12	5.45 ± 1.11	5.57 ± 1.12	5.58 ± 1.14
Group B	6.66 ± 1.83	6.76 ± 1.82	6.88 ± 1.87	6.98 ± 1.87	7.08 ± 1.87

Group C	6.09 ± 1.66	6.24 ± 1.67	6.32 ± 1.63	6.41 ± 1.62	6.52 ± 1.66
Group D	5.57 ± 1.27	5.79 ± 1.21	5.97 ± 1.19	6.18 ± 1.14	6.42 ± 1.15
Group E	6.04 ± 1.41	6.14 ± 1.41	6.33 ± 1.42	6.41 ± 1.34	6.42 ± 1.34

Group B showed the highest mean strength values at all time points, while Group D demonstrated notable improvement by the end of the intervention period. Group C had a consistent week-in week-out improvement as well. The difference in strength in Group A and

Group E showed comparative and non-significant recovery changes. On the whole, the results show that the quadriceps strength improvement was progressive in all of the groups throughout the intervention period.

Table 3. Within-group comparison of quadriceps strength progression following graded backward treadmill rehabilitation (Friedman test)

Groups	Pre test (Mean±SD)	Week-1 (Mean±SD)	Week-2 (Mean±SD)	Week-3 (Mean±SD)	Week-4 (Mean±SD)	χ ² value	p value
Group A	5.25 ± 1.13	5.38 ± 1.12	5.45 ± 1.11	5.57 ± 1.12	5.58 ± 1.14	36.704	<0.001
Group B	6.66 ± 1.83	6.76 ± 1.82	6.88 ± 1.87	6.98 ± 1.87	7.08 ± 1.87	33.677	<0.001
Group C	6.09 ± 1.66	6.24 ± 1.67	6.32 ± 1.63	6.41 ± 1.62	6.52 ± 1.66	43.748	<0.001
Group D	5.57 ± 1.27	5.79 ± 1.21	5.97 ± 1.19	6.18 ± 1.14	6.42 ± 1.15	42.564	<0.001
Group E	6.04 ± 1.41	6.14 ± 1.41	6.33 ± 1.42	6.41 ± 1.34	6.42 ± 1.34	42.968	<0.001

The Friedman test was used to examine improvements within groups, while the Kruskal-Wallis test was used to compare groups and evaluate changes among intervention groups. Table 3 is the within-group comparison of the quadriceps strength during the four weeks intervention period using the Friedman test. Mean quadriceps strength showed a progressive improvement of all groups (baseline and week-4). The statistical analysis indicated that the differences that were seen in the

individual groups were very significant ($p < 0.001$). Group C and Group E reported higher values of chi-square that showed their more strength as days progressed, whereas Groups A, B and D also reported other consistent and significant progress. These results show that, there was a considerable gain in quadriceps strength across the study period in all the groups due to the rehabilitation interventions.

Table 4. Between-group comparison of quadriceps strength across the intervention period following graded backward treadmill rehabilitation (Kruskal-Wallis test)

Outcome Measure	Group A (Mean±SD)	Group B (Mean±SD)	Group C (Mean±SD)	Group D (Mean±SD)	Group E (Mean±SD)	χ ² value	p value	Significance
Pre test	5.25 ±	6.66 ±	6.09 ±	5.57 ±	6.04 ±	5.31	0.25	NS

	1.13	1.83	1.66	1.27	1.41	6	6	
Week-1	5.38 ± 1.12	6.76 ± 1.82	6.24 ± 1.67	5.79 ± 1.21	6.14 ± 1.41	4.48 1	0.34 5	NS
Week-2	5.45 ± 1.11	6.88 ± 1.87	6.32 ± 1.63	5.97 ± 1.19	6.33 ± 1.42	4.83 9	0.30 4	NS
Week-3	5.57 ± 1.12	6.98 ± 1.87	6.41 ± 1.62	6.18 ± 1.14	6.41 ± 1.34	4.95 2	0.29 2	NS
Week-4	5.58 ± 1.14	7.08 ± 1.87	6.52 ± 1.66	6.42 ± 1.15	6.42 ± 1.34	6.11 9	0.19 0	NS

Table 4 presents the between-group comparison of quadriceps strength at baseline and at weekly follow-up assessments using the Kruskal–Wallis test. The results showed no statistically substantial differences between the five groups at baseline ($p=0.256$) or at the weekly measurements ($p>0.05$). The lack of statistically significant between-group differences can be explained by the fact that the sample size is rather small or groups are rather heterogeneous, which might have reduced the statistical strength to find the differences between the conditions of intervention. Although Group B demonstrated higher mean strength values and Group D showed greater improvement by the end of the intervention period, these differences were not statistically significant. These findings indicate that while all groups demonstrated improvement in quadriceps strength over time, the differences in strength recovery between the different treadmill inclination groups were not statistically significant.

Overall, all intervention groups demonstrated improvement in quadriceps strength following the rehabilitation program. No adverse events were reported during the intervention period. Backward treadmill walking at inclined levels demonstrated greater mean improvements compared to conventional rehabilitation; however, these differences were not statistically significant. Therefore, while all groups improved over time, superiority of any specific incline level could not be established.

Discussion

The present study investigated the dose–response trend between graded backward treadmill inclination and quadriceps strength recovery following anterior cruciate ligament reconstruction. The findings of this study demonstrated that all intervention groups showed progressive improvement in quadriceps strength over the four-week rehabilitation period. These findings are consistent with previous studies which reported that structured rehabilitation programs significantly improve quadriceps strength following ACL reconstruction [32–34].

Quadriceps weakness has been well-reported postoperative ACL reconstruction impairment that is largely explained by arthogenic muscle inhibition, decreased voluntary muscle activation and lack of mechanical loading during rehabilitation [35–37]. Quadriceps strength should be restored to enhance knee joint stability, functional performance and safe return to activity. The improvements in progressive strength that were evident in the study can be attributed to the neuromuscular aspects of backward treadmill walking that facilitates quadriceps muscle activation and motor control adjustments.

The findings of this study also demonstrated differences in the rate of strength recovery among the groups, indicating a potential descriptive tendency in the strength recovery patterns on various incline levels but no concluding dose to response relationship can be established because of the lack of statistically

significant between-group differences. Group B showed quicker progress in strength, implying that moderate loading could give an optimum stimulus to early strength recovery. Past studies indicate that moderate mechanical loading can increase neuromuscular activities without overloading or overstraining of the joints, which result in the early rehabilitation of strength [38-40].

Group D showed higher values of final strength at the end of the intervention period, which could be attributed to the increased mechanical demand that is related to higher levels of treadmill inclination. Raised incline ambulation has been known to raise quadriceps activation, metabolic demand and lower limb muscle recruitment, which is likely to stimulate additional strength adaptations ultimately [41-43]. These results coincide with the principle of progressive overload, nevertheless, in the fact of the absence of statistically significant between-group differences, one should take these results with a grain of salt, which reflects a fundamental concept in rehabilitation and strength training.

The current results are also in line with the existing research that indicates that backward walking stimulates more quadriceps muscle recruitment than forward walking because of the altered gait movement and enhanced concentric muscle actions [44,45]. The neuromuscular load in relation to walking backwards may thus be the reason behind the quadriceps strengthening in all interventions [46].

Clinically, the increase in quadriceps strength is directly linked with the increase in knee joint stability, better gait mechanics, and the decrease of the risk of re-instances after ACL reconstruction. Functional activities like walking, stair negotiation and returning to sport require adequate quadriceps strength [47-49]. Thus, the statistically insignificant between-group differences do not eliminate the presence of statistically significant improvements in all groups, which indicate the relevance of the

progressive rehabilitation strategies in the early post-operative recovery.

Although the current research relied on the strength of the quadriceps as the main outcome, functional recovery after ACL reconstruction is multivariate [50,51]. In future research studies, more outcome measures are necessary to include Lysholm Knee Score, International Knee Documentation Committee (IKDC) score, single-leg hop tests, and gait analysis to have a complete estimate of the effectiveness of rehabilitation [52].

Clinically, the results of study further propose that graded backward treadmill training might be considered as a potentially useful intervention for improving quadriceps strength following ACL reconstruction. The findings further suggest that moderate to higher treadmill inclinations may contribute to strength recovery when applied progressively and safely within rehabilitation programs. These findings may assist clinicians in designing progressive loading strategies for ACL rehabilitation based on patient tolerance and rehabilitation stage [53-55].

Limitations of the Study

The present study has certain limitations. The intervention duration was limited to four weeks and long-term strength adaptations were not evaluated. The sample size was relatively small and participants were not followed beyond the intervention period to determine long-term functional carryover. In addition, Because of the character of the intervention, participant and therapist blinding was not feasible. Future studies should investigate long-term strength adaptations, return-to-sport outcomes and optimal loading parameters for backward treadmill rehabilitation. Furthermore, the short duration of the intervention (4 weeks) limits the ability to assess long-term strength adaptations and functional recovery outcomes. Additionally, the study did not include functional outcome measures such as return-to-sport performance or patient-reported outcomes, which limits the clinical generalizability of the findings.

Conclusion

The findings of the present study demonstrate that quadriceps strength improved across all groups following the rehabilitation program. However, no statistically substantial differences were seen among groups. While descriptive trends in strength recovery were noted, a definitive dose–response relationship between treadmill inclination and strength recovery could not be established. Additional studies with larger sample sizes and longer follow-up are essential.

Clinical Implications

The results of study suggest that graded reverse treadmill walking may be adopted as a supportive strengthening intervention of an ACL rehabilitation program. During the initial

stages of rehabilitation process, moderate treadmill inclinations could be considered as advantageous as they will provide neuromuscular activation and progressive improvement of muscle strength whereas higher inclinations can be implemented gradually in order to boost muscle strength adjustments. Backward treadmill training offers a safe closed kinetic chain exercise which minimizes unwanted stress in the joints and enhances activation of the quadriceps. Thus, clinicians can put into consideration the use of graded backward treadmill protocols into the progressive rehabilitation programs to assist in recovery of strength and enhancing the rehabilitation outcomes after the ACL reconstruction is done.

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