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RELATIONSHIP BETWEEN QUADRICEPS MUSCLE THICKNESS, MUSCLE STRENGTH, KNEE FUNCTION, AND QUALITY OF LIFE FOLLOWING GRADED BACKWARD TREADMILL TRAINING AFTER ACL RECONSTRUCTION

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ABSTRACT
Background: Recovery after anterior cruciate ligament reconstruction (ACLR) is multidimensional. Quadriceps muscle atrophy and weakness may coexist with impaired knee function and reduced quality of life. Although graded backward treadmill training improves these outcomes, the relationships among structural muscle recovery, strength recovery, knee function, and ACL-specific quality of life require separate evaluation.
Objective: To determine the relationships between changes in quadriceps muscle thickness, quadriceps muscle strength, knee function, and quality of life following graded backward treadmill training after ACL reconstruction.
Methods: A secondary analysis was performed using participant-level data from 60 individuals, 3–6 months after unilateral arthroscopic ACL reconstruction with semitendinosus graft. Participants had been randomized into five groups (n=12 each): backward treadmill walking at 0°, 5°, 10°, or 15° inclination, or conventional rehabilitation. Training was delivered for 20 minutes per session, three sessions per week for four weeks. Quadriceps strength was assessed using a MicroFET handheld dynamometer, muscle thickness using musculoskeletal ultrasound, knee function using the International Knee Documentation Committee (IKDC) subjective knee form, and quality of life using the ACL-QOL questionnaire. Change scores were calculated as post-intervention minus baseline values. Because several change-score distributions were non-normal, Spearman rank correlations were used; 95% confidence intervals were estimated by bootstrap resampling.
Results: All groups improved across the four outcome domains. The 15° group showed the largest mean changes in strength (0.86±0.28), muscle thickness (0.64±0.64 cm), IKDC (31.88±12.17), and ACL-QOL (26.38±21.21). Across all 60 participants, increase in muscle thickness was weakly associated with strength gain ($\rho=0.266$, $p=0.040$). Strength gain was positively associated with IKDC improvement ($\rho=0.332$, $p=0.010$), and IKDC improvement was positively associated with ACL-QOL improvement ($\rho=0.357$, $p=0.005$). Muscle-thickness change was not significantly associated with IKDC or ACL-QOL change, and strength change was not significantly associated with ACL-QOL change. In exploratory regression adjusted for intervention group, strength and muscle-thickness changes were not independent predictors of IKDC change; IKDC change remained independently associated with ACL-QOL change (B=0.70, 95% CI 0.27–1.13, $p=0.001$).
Conclusion: Following ACL reconstruction, structural, strength, functional, and quality-of-life recovery appear related but are not interchangeable. Greater quadriceps strength recovery was associated with better knee-function improvement, while improvement in knee function showed the clearest relationship with improvement in ACL-specific quality of life. Multidimensional assessment using ultrasound, dynamometry, IKDC, and ACL-QOL may provide a more complete picture of rehabilitation progress.

KEYWORDS: anterior cruciate ligament reconstruction; backward walking; quadriceps muscle thickness; muscle strength; IKDC; ACL-QOL; rehabilitation

INTRODUCTION
Anterior cruciate ligament (ACL) reconstruction is commonly performed to restore mechanical stability of the knee. However, rehabilitation outcomes are frequently limited by persistent quadriceps weakness, muscle atrophy, altered neuromuscular control, and incomplete restoration of patient-perceived function1–4. Quadriceps capacity is clinically relevant because it contributes to shock absorption, dynamic knee stability, gait, stair negotiation, and progression toward higher-level activity.

Muscle strength and muscle morphology represent related but distinct dimensions of recovery. Strength may improve through neural and motor-control adaptations even before substantial hypertrophy occurs, while persistent reductions in muscle size can remain despite apparently satisfactory functional progress. Handheld dynamometry provides an objective estimate of force-generating capacity, whereas musculoskeletal ultrasound offers a practical method for monitoring muscle thickness and structural recovery 5,6.

Recovery after ACL reconstruction cannot be defined by impairment-level measures alone. The International Knee Documentation Committee (IKDC) subjective knee form evaluates symptoms and patient-perceived knee function, while the ACL Quality of Life (ACL-QOL) questionnaire captures the broader physical, psychological, recreational, and social effects of ACL injury 7–9. Evaluating these outcomes together may clarify whether improvements in quadriceps structure and strength translate into clinically meaningful functional and quality-of-life gains.

Backward treadmill walking is a closed kinetic chain strategy that alters lower-limb muscle recruitment and increases quadriceps demand. Increasing treadmill inclination may further increase mechanical loading and neuromuscular demand 10–12. The parent randomized controlled trial demonstrated improvements in quadriceps strength, muscle thickness, IKDC, and ACL-QOL following graded backward treadmill training, with the highest-incline group showing the largest mean improvements.

However, simultaneous improvement in several outcomes does not establish that improvement in one domain is directly related to improvement in another. Therefore, the present secondary analysis examined the relationships among quadriceps muscle-thickness change, strength recovery, knee-function improvement, and quality-of-life improvement after graded backward treadmill training following ACL reconstruction.

METHODOLOGY

Study Design and Ethics

This study was a secondary analysis of participant-level data from a prospective randomized controlled trial conducted in hospitals affiliated with Padmashree Institute of Physiotherapy. Ethical approval for the parent study was obtained from the Institutional Ethical Committee of Padmashree Institute of Physiotherapy (PIEC/28/2022) and the Central Ethical Committee, Nitte University (NU/CEC/2023/359). Written informed consent was obtained from all participants.

Participants

Sixty participants who had undergone unilateral arthroscopic ACL reconstruction using a semitendinosus graft were recruited 3–6 months postoperatively. Participants were in the active strengthening phase of rehabilitation and were able to walk independently. The parent trial excluded revision ACL reconstruction, inflammatory joint disease, neurological disorders, recent lower-limb fractures, associated ligament injuries, and other conditions affecting gait.

Randomization and intervention

Participants were randomly allocated using an opaque-envelope method to five groups (n=12 each). Group A performed backward treadmill walking at 0° inclination, Group B at 5°, Group C at 10°, and Group D at 15°. Group E received conventional physiotherapy rehabilitation. Backward treadmill walking was performed at a constant speed of 1.3 km/hour for 20 minutes per session, three times per week for four weeks. Standard rehabilitation exercises were continued.

Outcome measures

Quadriceps muscle strength was measured using a MicroFET handheld dynamometer. Quadriceps muscle thickness was assessed using real-time B-mode musculoskeletal ultrasound. Knee function was assessed using the IKDC Subjective Knee Evaluation Form, and ACL-specific quality of life using the ACL-QOL questionnaire. Strength was recorded at baseline and weekly; for the present analysis, baseline and week-4 values were used. Ultrasound, IKDC, and ACL-QOL were recorded before and after the four-week intervention.

Statistical analysis

Participant-level change scores were calculated as post-intervention minus baseline values for quadriceps strength (ΔStrength), ultrasound muscle thickness (ΔThickness), IKDC (ΔIKDC), and ACL-QOL (ΔACL-QOL). Distributional assumptions were assessed using the Shapiro–Wilk test. ΔStrength ($p=0.004$), ΔThickness ($p<0.001$), and ΔACL-QOL ($p<0.001$) were non-normally distributed, whereas ΔIKDC was approximately normally distributed ($p=0.217$). Accordingly, Spearman rank-order correlation was selected as the primary association analysis for all outcome pairs to maintain a consistent non-parametric approach. Bootstrap 95% confidence intervals were estimated using 10,000 resamples. Exploratory multivariable ordinary least-squares regression with heteroscedasticity-robust (HC3) standard errors was used to examine independent associations after accounting for intervention group. Statistical significance was set at $p<0.05$.

RESULTS

Participant Characteristics And Overall Change

All 60 randomized participants completed the parent trial. The dataset contained 12 participants in each of the five intervention groups. Baseline demographic and clinical characteristics were comparable across groups in the parent analysis.

Table 1. Overall pre-intervention, post-intervention, and change scores for the 60 participants.

Outcome	Baseline Mean ± SD	Post Mean ± SD	Change Mean ± SD
Quadriceps strength	5.92 ± 1.51	6.41 ± 1.49	0.49 ± 0.27
Muscle thickness (cm)	2.44 ± 0.70	2.74 ± 0.81	0.30 ± 0.41
IKDC	28.64 ± 8.43	52.80 ± 10.35	24.16 ± 9.59
ACL-QOL	20.02 ± 7.18	35.16 ± 12.99	15.14 ± 13.18

Changes according to intervention group

All five groups demonstrated improvement across the four recovery domains. Group D (15° backward treadmill inclination) demonstrated the largest mean improvement in quadriceps strength, muscle thickness, IKDC, and ACL-QOL.

Table 2. Mean ± SD change scores by treatment group.

Outcome change	Group A 0°	Group B 5°	Group C 10°	Group D 15°	Group E Control	ANOVA p
Δ Strength	0.33 ± 0.14	0.42 ± 0.22	0.43 ± 0.13	0.86 ± 0.28	0.38 ± 0.19	<0.001
Δ Thickness (cm)	0.15 ± 0.24	0.43 ± 0.44	0.18 ± 0.11	0.64 ± 0.64	0.11 ± 0.11	0.003
Δ IKDC	19.54 ± 7.29	24.58 ± 10.55	21.58 ± 6.67	31.88 ± 12.17	23.22 ± 6.29	0.016
Δ ACL-QOL	10.29 ± 3.10	15.61 ± 11.76	12.29 ± 4.66	26.38 ± 21.21	11.13 ± 11.02	0.012

Relationships among muscle structure, strength, function, and quality of life

The primary Spearman correlation analysis demonstrated three statistically significant positive relationships. Greater improvement in quadriceps muscle thickness was weakly associated with greater strength gain (ρ=0.266, p=0.040). Greater strength gain was associated with greater improvement in IKDC score (ρ=0.332, p=0.010). The strongest observed association was between IKDC improvement and ACL-QOL improvement (ρ=0.357, p=0.005). Muscle-thickness change was not significantly associated with IKDC or ACL-QOL change, and strength change was not significantly associated with ACL-QOL change.

Table 3. Participant-level relationships among change scores (n=60). Confidence intervals are percentile bootstrap intervals from 10,000 resamples.

Association	Spearman ρ	95% bootstrap CI	p value	Interpretation
Δ Thickness vs Δ Strength	0.266	0.008 to 0.505	0.040	Weak positive; significant
Δ Thickness vs Δ IKDC	0.222	−0.059 to 0.490	0.088	Weak positive; not significant
Δ Thickness vs Δ ACL-QOL	0.054	−0.195 to 0.304	0.681	Negligible; not significant
Δ Strength vs Δ IKDC	0.332	0.043 to 0.585	0.010	Weak-to-moderate positive; significant
Δ Strength vs Δ ACL-QOL	0.108	−0.168 to 0.374	0.413	Weak; not significant
Δ IKDC vs Δ ACL-QOL	0.357	0.089 to 0.583	0.005	Moderate positive; significant

Exploratory multivariable analysis

In the model predicting ΔIKDC, the overall model explained 23.5% of the variance (R^2=0.235; adjusted R^2=0.148). After adjustment for intervention group and simultaneous inclusion of ΔStrength and ΔThickness, neither ΔStrength

(B=7.93, 95% CI −4.78 to 20.65, p=0.221) nor ΔThickness (B=2.69, 95% CI −4.82 to 10.20, p=0.483) remained independently associated with ΔIKDC.

In the exploratory model predicting ΔACL-QOL, the model explained 42.0% of the variance (R^2=0.420; adjusted R^2=0.342). ΔIKDC remained independently associated with ΔACL-QOL (B=0.70, 95% CI 0.27 to 1.13, p=0.001). ΔStrength and ΔThickness were not independent predictors. Relative to Group A, Group D showed a higher adjusted ACL-QOL change (B=15.14, 95% CI 1.04 to 29.25, p=0.035); other group contrasts were not significant. Because these models are secondary and the sample size is modest, they should be interpreted as exploratory.

DISCUSSION

The present secondary analysis evaluated recovery after ACL reconstruction as an integrated structure–strength–function–quality-of-life process. The parent trial showed improvement across all four domains, and participants trained at 15° backward treadmill inclination demonstrated the largest mean gains. The new participant-level analysis adds an important finding: improvements in muscle structure, muscle strength, knee function, and quality of life were only partly related to one another.

A statistically significant but weak positive relationship was observed between increase in quadriceps muscle thickness and strength gain. This finding is clinically plausible because greater muscle size may contribute to force-generating capacity, but the modest correlation indicates that hypertrophy alone does not explain strength recovery. Neural activation, arthrogenic muscle inhibition, pain, motor control, and task-specific adaptations may also influence post-ACLR strength [3–6].

Quadriceps strength gain showed a significant positive relationship with IKDC improvement. This supports the clinical relevance of quadriceps recovery for patient-perceived knee function. Nevertheless, the association was only weak to moderate, and it did not remain independently significant after adjustment for treatment group and muscle-thickness change. Knee function after ACL reconstruction is multifactorial and depends not only on strength but also on symptoms, proprioception, movement quality, confidence, and neuromuscular control 2–4,13.

The relationship between IKDC improvement and ACL-QOL improvement was the clearest functional association in the study. This suggests that patients who perceived greater recovery in knee symptoms and function also tended to report greater improvement in ACL-specific quality of life. In the exploratory adjusted model, IKDC change remained independently associated with ACL-QOL change. This reinforces the concept that quality of life after ACL reconstruction is closely connected to the patient's functional experience rather than to an isolated impairment measure.

Interestingly, neither muscle-thickness change nor strength change demonstrated a significant direct relationship with ACL-QOL improvement. This does not imply that muscular recovery is unimportant. Rather, the influence of muscle recovery on quality of life may be indirect, operating through improved knee function, confidence, activity participation, and symptom reduction. A simple one-to-one relationship between structural recovery and quality of life should therefore not be assumed.

The findings support a multidimensional approach to ACL rehabilitation assessment. Ultrasound can document structural quadriceps recovery, handheld dynamometry quantifies strength, IKDC captures symptoms and knee function, and ACL-QOL reflects the broader patient experience. Because these measures provide complementary rather than redundant information, combining them may offer a more complete assessment of rehabilitation progress.

The study has several limitations. First, the present analysis was secondary and was not the primary basis for the original sample-size calculation. Second, the total sample was modest, limiting the number of variables that could be included in multivariable models. Third, the follow-up period was limited to four weeks, and no long-term return-to-sport or reinjury outcomes were available. Fourth, pooled correlations can be influenced by intervention-group differences; the exploratory regression models were therefore adjusted for group, but residual confounding remains possible. Finally, association does not establish causation even though the data originated from a randomized trial, because the change variables themselves were not randomized.

Clinical Implications

Quadriceps muscle-thickness improvement and strength recovery are related, although the relationship is modest, suggesting that both parameters should be assessed when feasible to obtain a comprehensive understanding of muscular recovery. Greater quadriceps strength recovery is associated with better patient-perceived knee function, highlighting the importance of restoring muscle strength during ACL rehabilitation. Furthermore, improvement in knee function appears to be more closely related to ACL-specific quality-of-life improvement than isolated changes in muscle structure or strength. Therefore, ultrasound assessment of muscle thickness, dynamometry for muscle strength, IKDC for knee function, and ACL-QOL for quality of life should be considered complementary rather than interchangeable outcome measures, as each evaluates a distinct dimension of recovery following ACL reconstruction.

CONCLUSION

Following graded backward treadmill rehabilitation after ACL reconstruction, quadriceps muscle thickness, muscle strength, knee function, and quality of life improved concurrently, with the 15° backward-walking group showing the largest mean gains. Participant-level analysis demonstrated a weak positive association between muscle-thickness gain and strength gain, a positive association between strength recovery and IKDC improvement, and the strongest relationship between IKDC improvement and ACL-QOL improvement. These findings indicate that structural, strength, functional, and quality-of-life recovery are related but represent distinct dimensions of rehabilitation. Multidimensional monitoring may therefore provide a more clinically meaningful picture of recovery than reliance on a single outcome measure.

Declarations

Ethical approval: Institutional Ethical Committee, Padmashree Institute of Physiotherapy: PIEC/28/2022; Central Ethical Committee, Nitte University: NU/CEC/2023/359.

Informed consent: Written informed consent was obtained from all participants in the parent trial.

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Conflict of interest: No Conflict of Interest.

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