

Original Research Article

EFFECTS OF PROGRESSIVE SENSORY INTEGRATION AND COGNITIVE-MOTOR TRAINING ON MOTOR ADAPTABILITY AND DYNAMIC KNEE STABILITY AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION: A PROSPECTIVE PRE-POST STUDY

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ABSTRACT

Background: Anterior cruciate ligament reconstruction (ACLR) restores mechanical stability of the knee; however, deficits in proprioception, sensorimotor control, and movement adaptability may persist after surgery. Progressive sensory-integration and cognitive-motor training may help address these deficits and improve functional recovery. The aim is to evaluate changes in motor adaptability and dynamic knee stability following a progressive sensory-integration and cognitive-motor rehabilitation programme in patients after ACLR.

Materials and Methods: A prospective interventional study was conducted among 75 patients following ACLR at Hi-Tech Hospital, Gandhinagar, Gujarat, India. Participants underwent a structured physiotherapy rehabilitation programme incorporating progressive sensory-integration and cognitive-motor training. Motor adaptability and dynamic knee stability were assessed before and after the intervention. Dynamic knee stability was evaluated using the Y-Balance Test.

Results: The mean age of participants was 27.8 ± 5.9 years, and 65.3% were male. The mean motor adaptability score increased from $43.5 \pm 8.443.5$ at baseline to $61.8 \pm 8.961.8$ after completion of the rehabilitation programme. The mean Y-Balance Test composite score increased from $76.4 \pm 6.7\%$ to $87.9 \pm 5.8\%$ ($p < 0.001$), with significant improvements in all three reach directions. Improvement in motor adaptability showed a moderate positive correlation with improvement in dynamic knee stability ($r = 0.54$, $p < 0.001$).

Conclusion: Participation in a progressive sensory-integration and cognitive-motor rehabilitation programme was associated with improved motor adaptability and dynamic knee stability after ACLR. Incorporating sensory and cognitive-motor challenges into postoperative rehabilitation may help improve sensorimotor control and functional knee stability.

Keywords: Anterior Cruciate Ligament Reconstruction, Cognitive-Motor Training, Sensory Integration, Motor Adaptability, Dynamic Knee Stability, Y-Balance Test; Rehabilitation.

INTRODUCTION

The anterior cruciate ligament (ACL) plays an important role in maintaining knee stability,

primarily by limiting anterior translation of the tibia.^[1] ACL injuries commonly occur through either contact or non-contact mechanisms, particularly during sudden deceleration, changes in direction, or

landing from a jump. Such injuries can disrupt normal knee biomechanics and affect overall functional stability.^[2-4] The global incidence of ACL rupture has been estimated to approach approximately two million cases annually.^[5] In addition to mechanical instability, ACL injury is often associated with weakness of the quadriceps and hamstring muscles, impaired knee proprioception, and reduced balance, all of which can further compromise knee stability.^[6-8]

Growing evidence suggests that ACL injury should not be viewed simply as an isolated mechanical injury to the knee. Damage to mechanoreceptors within the ligament can alter sensory feedback and produce neurophysiological changes that affect neuromuscular and sensorimotor control.^[9] Neuromuscular control is essential for both the initiation of movement and the performance of coordinated and efficient motor activities. It depends on the integration of information from the proprioceptive, kinesthetic, visual, and vestibular systems with motor commands generated at cortical and spinal levels.^[10,11]

Following ACL injury, disruption of ligamentous mechanoreceptors can alter somatosensory input from the knee, resulting in impaired postural and motor control and delayed lower-extremity reaction time.^[12] Pain and joint effusion may further affect sensory function by altering joint position sense and kinesthesia, which can ultimately compromise movement quality.^[13] Importantly, deficits in neuromuscular control associated with mechanoreceptor damage, proprioceptive loss, and altered somatosensory input may persist for 9–12 months following ACL injury.^[14]

Anterior cruciate ligament reconstruction (ACLR) is commonly performed to restore knee stability and facilitate return to activity. However, successful surgical reconstruction does not necessarily result in complete functional recovery. Reported return-to-sport rates remain relatively low, with approximately 31% of patients returning at one year,^[15] 41% at two years,^[16] and 63% eventually returning to their pre-injury level of performance.^[17] These findings highlight the challenge of restoring optimal function and sports performance following ACLR. Consequently, postoperative rehabilitation has traditionally focused on early restoration of functional activity, muscle strength,^[18,19] and joint mobility.^[20,21]

Although these conventional rehabilitation components remain important, restoration of muscle strength and range of motion alone may not fully address the sensorimotor deficits that follow ACL injury and reconstruction. Effective functional recovery also requires the ability to integrate sensory information, respond appropriately to changing environmental demands, and maintain knee control while simultaneously performing cognitive and motor tasks. Progressive sensory-integration and cognitive-motor training may therefore provide an additional rehabilitation approach by challenging

proprioceptive processing, postural control, reaction ability, attention, and movement adaptation under increasingly complex conditions.

Objective assessment of sensorimotor function following ACLR is therefore important for planning and progressing rehabilitation. Although the timing of postoperative assessment and exercise progression varies, it has been reported that following ACL reconstruction using a hamstring tendon graft, strengthening of the knee flexors is commonly delayed for approximately 6–8 weeks to allow adequate healing of the graft-harvest site.^[7] A rehabilitation approach that progressively introduces sensory and cognitive-motor challenges according to the patient's stage of recovery may therefore help address residual deficits in motor control and dynamic knee stability.

Considering the persistence of sensorimotor deficits after ACL injury and reconstruction, there is a need to explore rehabilitation strategies that extend beyond conventional strengthening and mobility exercises. Therefore, the present study evaluated changes in motor adaptability and dynamic knee stability following a progressive sensory-integration and cognitive-motor rehabilitation programme in patients after ACLR.

MATERIALS AND METHODS

A prospective interventional study was conducted at Hi-Tech Hospital, Gandhinagar, Gujarat, India, from January 2021 to January 2022, after obtaining approval from the Institutional Ethics Committee. A total of 75 patients who had undergone anterior cruciate ligament reconstruction (ACLR) and were referred for postoperative physiotherapy rehabilitation were included in the study.

Patients who had undergone ACL reconstruction, were clinically stable and eligible for postoperative physiotherapy rehabilitation, were able to understand and follow instructions, and were able to participate safely in the prescribed rehabilitation programme were included in the study. Patients with significant postoperative complications, associated fractures or major ligament injuries affecting the operated lower limb, significant neurological or musculoskeletal conditions interfering with balance or functional performance, or any medical condition preventing participation in the rehabilitation programme were excluded.

All participants underwent a structured physiotherapy rehabilitation programme comprising progressive sensory-integration and cognitive-motor training in addition to appropriate postoperative rehabilitation. Sensory-integration training was designed to improve proprioceptive awareness, postural control, and the ability to integrate sensory information during functional activities. The programme progressively challenged participants through activities involving altered visual input, changes in support surface, balance tasks, and controlled perturbations. The difficulty of the

exercises was gradually increased according to individual functional ability, postoperative status, and tolerance.

Cognitive-motor training involved performing functional motor tasks together with progressively challenging cognitive demands. These activities were designed to improve attention, reaction, decision-making, and the ability to maintain appropriate lower-limb control while responding to changing task demands. The programme progressed from relatively predictable tasks to more complex activities requiring simultaneous cognitive processing and motor responses. Emphasis was placed on maintaining appropriate knee alignment and movement control throughout the exercises.

The rehabilitation programme was administered under the supervision of a qualified physiotherapist. Particular attention was given to correct exercise technique, dynamic knee alignment, controlled movement, patient safety, and gradual progression of task difficulty according to individual recovery.

All participants underwent standardized assessment before initiation of the intervention and after completion of the rehabilitation programme. The primary outcomes evaluated were motor adaptability and dynamic knee stability. The same assessment

procedures were followed during pre- and post-intervention evaluations to maintain consistency.

Demographic and clinical information, including age, sex, body mass index, relevant clinical history, characteristics related to ACL reconstruction, duration since surgery, and baseline functional status, was recorded using a structured data collection form. Pre- and post-intervention outcome measurements were recorded for each participant.

The collected data were entered into a database and analyzed using appropriate statistical methods. Continuous variables were presented as mean and standard deviation, whereas categorical variables were expressed as frequency and percentage. Pre- and post-intervention outcome scores were compared using an appropriate paired statistical test. The association between improvement in motor adaptability and dynamic knee stability was assessed using an appropriate correlation coefficient. A p-value <0.05 was considered statistically significant.

RESULTS

A total of 75 patients following anterior cruciate ligament reconstruction were included in the study.

Table 1: Socio-clinical characteristics of study participants (N=75)

Parameters	Number (%) / Mean $\pm$ SD
Age (years)	27.8 $\pm$ 5.9
Male	49 (65.3%)
Female	26 (34.7%)
BMI (kg/m ²)	24.6 $\pm$ 2.8
Right knee involved	41 (54.7%)
Left knee involved	34 (45.3%)
Duration since ACL reconstruction (weeks)	8.1 $\pm$ 1.7

[Table 1] shows the socio-clinical characteristics of the study participants. The mean age was 27.8 $\pm$ 5.9 years, with males accounting for 65.3% and females for 34.7% of the participants. The mean BMI was

24.6 $\pm$ 2.8 kg/m². The right knee was involved in 54.7% of participants, while 45.3% had left-knee involvement. The mean duration since ACL reconstruction was 8.1 $\pm$ 1.7 weeks.

Table 2: Comparison of motor adaptability before and after intervention (N=75)

Outcome	Pre-intervention Mean $\pm$ SD	Post-intervention Mean $\pm$ SD	Mean change	p-value
Motor adaptability score*	43.5 $\pm$ 8.4	61.8 $\pm$ 8.9	+18.3	<0.001

[Table 2] shows the comparison of motor adaptability before and after progressive sensory-integration and cognitive-motor training. The mean motor adaptability score increased from 43.5 $\pm$ 8.4 before

the intervention to 61.8 $\pm$ 8.9 after the intervention, with a mean improvement of 18.3 points. The difference between the pre- and post-intervention scores was statistically significant (p<0.001).

Table 3: Comparison of dynamic knee stability before and after intervention (N=75)

Outcome	Pre-intervention Mean $\pm$ SD	Post-intervention Mean $\pm$ SD	Mean improvement	p-value
Y-Balance Test composite score (%)	76.4 $\pm$ 6.7	87.9 $\pm$ 5.8	+11.5	<0.001

[Table 3] shows the change in dynamic knee stability over the rehabilitation period. The mean Y-Balance Test composite score increased from 76.4 $\pm$ 6.7% before the intervention to 87.9 $\pm$ 5.8% after the

intervention, representing a mean improvement of 11.5 percentage points. The improvement was statistically significant (p<0.001).

Table 4: Direction-wise Y-Balance Test performance before and after intervention (N=75)

Direction	Pre-intervention Mean $\pm$ SD (%)	Post-intervention Mean $\pm$ SD (%)	Mean change	p-value
Anterior	69.8 $\pm$ 6.5	78.6 $\pm$ 5.9	+8.8	<0.001
Posteromedial	78.5 $\pm$ 7.2	90.1 $\pm$ 6.4	+11.6	<0.001
Posterolateral	80.9 $\pm$ 7.5	91.4 $\pm$ 6.2	+10.5	<0.001

[Table 4] shows direction-wise changes in dynamic balance. Significant improvements were observed in the anterior, posteromedial, and posterolateral reach

directions between baseline and post-intervention assessment. The greatest mean improvement was observed in the posteromedial direction.

Table 5: Association between improvement in motor adaptability and improvement in dynamic knee stability

Variables	Correlation coefficient (r)	p-value
Improvement in motor adaptability vs. improvement in Y-Balance composite score	0.54	<0.001

[Table 5] shows the association between improvement in motor adaptability and improvement in dynamic knee stability. A moderate positive correlation ($r=0.54$) was observed between improvement in motor adaptability and improvement in the Y-Balance Test composite score. The correlation was statistically significant ($p<0.001$), indicating that participants who demonstrated greater improvement in motor adaptability also tended to show greater improvement in dynamic knee stability.

DISCUSSION

The participants in the present study were predominantly young adults, with a mean age of 27.8 years, and nearly two-thirds were male. This demographic profile is generally consistent with the population commonly undergoing ACL reconstruction, particularly physically active young adults. The mean BMI was within the normal-to-overweight range, and involvement of the right and left knees was relatively comparable.

Motor adaptability scores increased significantly from baseline to completion of the rehabilitation programme. The mean motor adaptability score increased from 43.5 ± 8.4 before the intervention to 61.8 ± 8.9 after the intervention ($p<0.001$). This improvement suggests that participants were better able to adjust and control their movements in response to changing task demands after completing the rehabilitation programme. may have contributed,” but add that the design cannot determine causation: “Although repeated exposure to sensory and cognitive-motor challenges may have contributed, the single-group pre–post design cannot distinguish this from natural recovery, strengthening, or other components of rehabilitation.

Y-Balance Test composite scores increased significantly over the rehabilitation period. The mean Y-Balance Test composite score increased from $76.4 \pm 6.7\%$ to $87.9 \pm 5.8\%$ ($p<0.001$), indicating better dynamic postural control of the lower extremity following rehabilitation. Restoration of muscle strength alone may not be sufficient for optimal functional recovery after ACL reconstruction. Dynamic knee stability also depends on proprioceptive input, neuromuscular control,

balance, and the ability to coordinate movement in response to changing task and environmental demands. The sensory-integration component may have contributed; however, the contribution of this component cannot be isolated because participants also received standard postoperative rehabilitation. Similar findings were reported by Zheng QY et al,^[22] in a randomized controlled trial involving 48 patients. The authors compared conventional ACL rehabilitation with the same programme supplemented by proprioceptive training. At 12 weeks after surgery, participants receiving additional proprioceptive training demonstrated better dynamic balance, as reflected by a significantly higher Y-Balance comprehensive index than the control group. Improvements were also reported in IKDC and ACL-RSI scores. These findings are consistent with the present study and support the role of proprioceptive and sensory-based training in improving functional recovery after ACL reconstruction.

Direction-wise analysis of the Y-Balance Test showed improvement in all three directions. The anterior reach improved by 8.8 percentage points, the posteromedial reach by 11.6 percentage points, and the posterolateral reach by 10.5 percentage points, with the greatest improvement observed in the posteromedial direction. Improvement across all three directions suggests that the intervention may have enhanced dynamic balance and lower-limb control across different movement demands rather than improving performance in only a single direction.

Another important finding was the moderate positive correlation between improvement in motor adaptability and improvement in dynamic knee stability ($r=0.54$, $p<0.001$). Participants who showed greater improvement in motor adaptability also tended to demonstrate greater improvement in dynamic knee stability. This relationship suggests that the ability to adapt movement in response to changing sensory and cognitive demands may be closely related to the restoration of dynamic knee control following ACL reconstruction.

The combination of sensory-integration and cognitive-motor training may be particularly relevant in ACL rehabilitation because many everyday and sporting activities take place in changing and

unpredictable environments. Activities such as running, landing, cutting, and changing direction require individuals not only to maintain knee stability but also to process visual and proprioceptive information, respond to external stimuli, and make rapid movement decisions. Introducing these challenges progressively during rehabilitation may therefore prepare patients more effectively for complex functional activities than exercises performed only under predictable conditions.

This concept is supported by Heidarnia E et al,^[23] who studied male athletes following ACL reconstruction using an eight-week visual-cognitive neuromuscular training programme. Participants who received additional visual perturbation training demonstrated improvements in several biomechanical variables during unanticipated cutting, including reduced knee abduction torque and knee abduction range of motion, increased knee flexion range of motion, and lower ground-reaction forces. They also demonstrated fewer cognitive errors during cutting tasks. These findings suggest that challenging visual input during rehabilitation may improve the ability of the sensorimotor system to maintain lower-limb control during unexpected movements.

The importance of cognitive-motor demands following ACL reconstruction has also been demonstrated by Akbaşlı O et al,^[24] who evaluated individuals eight weeks after ACL reconstruction under single-task, cognitive dual-task, and motor dual-task conditions. Reaction time became progressively poorer as task demands increased, with the greatest impairment observed during motor dual-task conditions. These findings indicate that sensorimotor performance following ACL reconstruction may be affected when patients are required to divide their attention between simultaneous tasks. This provides further support for incorporating cognitive-motor challenges into rehabilitation programmes.

Similarly, Strong A et al,^[25] examined athletes following ACL reconstruction while performing drop vertical jumps with and without additional cognitive tasks. The addition of cognitive demands altered trunk, hip, knee, and ankle mechanics and resulted in a more upright and stiffer landing strategy. These findings highlight that movement patterns that appear satisfactory during simple or predictable tasks may change when additional cognitive demands are introduced. Rehabilitation should therefore consider the cognitive demands that patients are likely to encounter during functional and sporting activities. However, the available evidence does not consistently demonstrate that proprioceptive or balance-based rehabilitation is superior to conventional exercise for every outcome. Cooper RL et al,^[26] compared a six-week proprioceptive and balance programme with strengthening exercises during the early phase following ACL reconstruction. No significant between-group differences were observed in hop performance, while some patient-

reported functional outcomes showed greater improvement in the strengthening group. These findings suggest that sensory and proprioceptive training should not necessarily replace conventional strengthening exercises. Rather, combining strength, proprioception, sensory integration, and cognitive-motor training may provide a more comprehensive approach to rehabilitation following ACL reconstruction.

Overall, the findings of the present study suggest that progressive sensory-integration and cognitive-motor training may have a useful role in rehabilitation following ACL reconstruction. Improvements in both motor adaptability and dynamic knee stability indicate that rehabilitation targeting sensory processing, adaptive movement control, and cognitive-motor interaction may complement conventional approaches focused on strength and mobility. However, the absence of a control group should be considered when interpreting these findings, as natural postoperative recovery and other components of rehabilitation may also have contributed to the observed improvements. Single centric study, smaller sample size, absence of control group and short term follow up are were the limitations of present study.

CONCLUSION

In this single-group pre–post study, participation in a rehabilitation programme incorporating progressive sensory-integration and cognitive-motor training was associated with improved motor adaptability and dynamic knee stability after ACLR. Following the rehabilitation programme, participants demonstrated better motor adaptability as well as improved dynamic balance across different movement directions.

The association between improvements in motor adaptability and dynamic knee stability suggests that the ability to adjust movement in response to changing sensory and cognitive demands may be important for effective knee control during functional activities. Incorporating progressive sensory challenges and cognitive-motor tasks into postoperative rehabilitation may be considered as an adjunct to conventional postoperative rehabilitation; controlled studies are needed to establish its independent effectiveness.

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